Olesen Ingrid (Orcid ID: 0000-0001-9786-3379)

Policies to promote breeding for lice-resistant salmon – incentives designed for resilient and sustainable growth in aquaculture?

Kristin Rosendal[1], Anne Kettunen[2] and Ingrid Olesen[2]*

[1]The Fridtjof Nansen Institute (FNI), PB 326, NO-1326 Lysaker, Norway

[2] Nofima AS, P.O. Box 210, NO-1431 Ås, Norway

**e-mail: ingrid.olesen@nofima.no*

Abstract

Sea lice represent a persistent and growing problem, challenging the resilience and growth of the salmon aquaculture industry. In this Norwegian case study, we studied and discuss how the absence of policy instruments directed at stimulating breeding for lice resistance (LR) might be explained. We found well-documented opportunities for selection progress for LR. Hence, breeding on LR appears with an untapped potential. We discuss how market-based, legal, institutional, and interest-based factors can explain this.

Methodologically, we obtained data from document and literature studies and interviews with key players (salmon breeders, farmers, NGOs and governmental bodies in Norway).

First, LR is a polygenic trait, that makes it poorly suited for patenting. Furthermore, if only a small proportion of fish farmers choose seeds with higher LR, other operators can easily take on the free-rider role, because they will not suffer from reduced gain in growth performance, as a result of a much stronger emphasis on LR in the breeding goal. The market is thus hardly expected to stimulate stronger selection for LR in Norwegian salmon breeding. Second, neither genetic engineering (e.g. gene editing), still struggling with consumer acceptance, nor the uncertainty associated with possible changes in the Norwegian Gene Technology Act stimulate investment in LR via e.g. CRISPR technology. Thirdly, public policy instruments in their entirety have targeted other types of innovations against salmon lice, and none have so far been used to stimulate breeding companies to emphasize LR more strongly in their breeding programs. From a political point of view, it seems that breeding has been left to the market and the private sector. However, neither the NGOs nor the public seem to be aware of, or pay significant attention to the breeding potential to improve LR and fish welfare. Fragmented management of the aquaculture sector can camouflage the close ties between political and business interests. The industry is hesitant to invest significantly in long-term breeding targets such as significantly higher genetic LR. This may strengthen the assumption that strong economic interests will reduce the role of science in knowledge-based management. As farmed salmon are increasingly being exposed to stressful delousing treatments, mortality and associated welfare problems have increased significantly. For instance, large fish die more often from CMS (cardiomyopathy syndrome). The result is growing demand for CMS-resistant salmon. This gives rise to a paradoxical situation: increasing treatments with high mortality and fish welfare issues in farmed salmon, while the lice threat to wild salmon persists.

1. Introduction

Sea lice infestations have become a major and persistent problem that obstructs sustainable production increases in Atlantic salmon (*Salmo salar*) farming in Norway. Such infestations have serious environmental and health impacts, also on wild fish; moreover, they reduce fish farmers' incomes significantly, and limit production expansion of the salmon industry. The

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/jfb.15470

proliferation of sea lice is not the only problematic aspect of aquaculture, but here we focus on sea lice, as this problem has received the greatest regulatory attention, and because delousing treatments have become a major cause of welfare problems and mortality in farmed fish (Hjeltnes *et al.,* 2019; Sommerseth *et al.*, 2022).

The Norwegian government agrees with commercial actors on the goal of significantly increasing the sustainable production of farmed salmon (NFD, 2021), with reduced lice infestation seen as a major part of the solution. However, despite various policy incentives and targeted instruments, the aquaculture sector has failed to reduce sea lice problems sufficiently to enable significant increases in production. Indeed, according to the Norwegian Institute of Marine Research (Nilsen *et al.*, 2021) lice infestations in 2020 reached the highest level in the past 4 to 5 years, constituting a serious threat also to wild salmonids. Rosendal and Olesen (2022) discussed the pros and cons of selecting for lice resistance (LR) salmon, as also referred in section 3.2. (The state of breeding for LR: enhanced agreement). They concluded that from a collective action perspective and based on its public-good character, such biological innovation would need stimulation through the design of policy instruments and targeted government interventions. Furthermore, if all farmers and breeders then chose to add and adopt lice resistance, the reduced gain in growth would be carried equally by all, and everybody would contribute to and benefit from the positive effects of the ensuing lice reduction (Greaker et al., 2020).

In this study, we review and examine cognitive, political, and regulatory constraints and opportunities for reducing lice in farmed salmon in Norway, and the policies and regulations that affect breeding for LR. Previous studies, particularly those of Rosendal and Olesen (2022), have indicated an underexploited gap in selective breeding for fish resilience by improved LR salmon roe. We discuss how this gap can be explained and perhaps addressed.

Rosendal and Olesen (2022) examined how salmon farmers and breeders perceive the scope for and constraints on choosing LR salmon roe as a strategy for sustainable farming and breeding. Their analysis showed an acknowledged but underexploited potential for enhancing LR through selective breeding. However, interviews with salmon breeders and farmers indicated agreement that market-based factors would not suffice to stimulate further LR in breeding, and that technological quick-fixes through, e.g., CRISPR, are not seen as imminent. Delousing treatments are applied to comply with the regulatory demand for a maximum average of 0.5 adult female lice per fish. The roe available on the market has limited resistance to sea lice, and a significant increase in resistance would be required to reduce the number of delousing treatments. This has given rise to a 'hen-and-egg' situation, where there is scarce fish-farmer demand for the current type of LR roe, which in turn means few incentives for breeders to increase the selection pressure on LR in their breeding programmes in order to encourage greater demand for and sales of LR roe (Rosendal & Olesen, 2022). Instead, there has been a significant increase in the frequency of delousing treatments (Hjeltnes *et al.*, 2019; Sommerseth *et al.,* 2022).

Delousing treatments involving handling (including pharmaceutical, thermic and mechanical) generate severe stress to the salmon and cause increased mortality due to stress-related diseases, such as cardiomyopathy syndrome (CMS). The occurrence of losses from CMS has increased in parallel with more frequent delousing treatments (Hjeltnes *et al.,* 2019; Sommerseth *et al.,* 2022). CMS outbreaks entail serious economic losses, as outbreaks typically occur during the late phase of the production cycle with large-sized salmon almost ready for slaughter, when most production costs have already been incurred. In addition to the general stress, delousing treatments are likely to cause damage in the mucus, scales, and skin, rendering the fish prone to secondary infections. In fact, wounds caused by mechanical delousing treatments were reported as the main welfare problem of farmed salmon in a survey of fish health personnel in most production areas in 2021 (Sommerseth *et al.,* 2022).

Instead of seeking breeding solutions for lice resistance, farmers might focus on fish material that tolerates even more frequent delousing treatments. In practice, this translates into farmer demand for more CMS-resistant salmon roe (Rosendal & Olesen, 2022). Whereas LR shows polygenic variation, two genomic regions (QTLs) responsible for a substantial proportion of the genetic variance in CMS resistance have been identified. Hence, marker-assisted, or genomic, selection is expected to result in faster genetic improvement in CMS resistance than in LR (Hillestad & Moghadam, 2019; Boison *et al.,* 2019; Hillestad *et al.,* 2020). If breeding companies profit more from delivering CMS-resistant roe than LR roe, a paradoxical situation may arise, where salmon are exposed to more frequent mechanical treatments – with serious negative welfare implications – while the lice problem persists.

This provides the backdrop for our research question of whether policy incentives could have been employed to enhance innovation in LR breeding (to ensure fish welfare in line with Norway's Animal Welfare Act). In this study we investigate the regulatory and governance aspects of the salmon aquaculture sector.

There are many possible solutions to the sea lice problem. Here we need to consider the various types of innovations aimed at sea lice reduction: their challenges and potentials. Greaker and colleagues (2020) identify four types: delousing treatments, biological, mechanical, and genetic types of innovation.

First, the use of pharmaceutical delousing treatments has declined – because of the negative environmental effect, and because the lice have become less sensitive to the substances employed (Bechmann *et al.,* 2019; Olaussen, 2018). As a result, the use of thermic and mechanical delousing treatments has soared, despite the frequent and serious negative impacts on fish welfare (Hjeltnes *et al.,* 2019; Sommerseth *et al.,* 2022).

Second, the extensive use of cleaner-fish for eating the lice, most commonly lumpfish (*Cyclopterus lumpus*) or ballan wrasse (*Labrus bergylta*), is increasingly questioned because of health and welfare problems among the cleaner-fish (Hjeltnes *et al.,* 2019; Sommerseth *et al.,* 2022).

Third, more demanding mechanical/technical types of innovation, including offshore and on-land production, are not widely used by farmers, but can reduce the advantages offered by Norwegian fjords and further undermine coastal settlements (Greaker *et al.*, 2020; Larsen & Vormedal*,* 2021). Mechanical technologies have been specifically targeted by Norwegian policy instruments; development licences have all been issued for this type of innovation (Larsen & Vormedal*,* 2021).

Finally, the genetic type of innovation – breeding for LR – might avoid some or all these problems, but there are no policy instruments specifically aimed at this type of innovation that address the root cause of the lice problem (Rosendal & Olesen, 2022).

Against this backdrop, we ask:

How may the lack of policy instruments directed at stimulating breeding for LR fish be explained?

Here we examine the cognitive, political, and organizational context in which policy instruments are developed. First, we explain our analytical approach to evaluating explanations for why policy instruments have not been applied and aimed at stimulating LR in breeding. Then we present an empirical description of the state of LR breeding and the main actors involved. Next, we discuss how various factors may account for the lack of policies and how the issue of LR breeding might be addressed in policies and regulation.

2. Analytical framework and methodology

2.1 Analytical framework

The focus of this study is on policies (regulations and instruments) enacted to respond to the environmental challenges of sea lice infestations in Norwegian salmon farming. We note Norway's Traffic Light System (TLS) and the Development, Research, and Broodstock licenses, through which considerable government resources and attention to combating sea lice infestations have been directed since 2015. Asking why these policies have not been applied to stimulate breeding for LR, we examine the underlying cognitive, political, and organizational contexts.

Scientific uncertainties associated with environmental challenges have directed attention towards the relationship between science and politics (Andresen *et al.*, 2000). Despite political consensus that the management and regulation of aquaculture should be knowledge-based, the management and regulation of environmental challenges have not necessarily followed scientific knowledge and advice. Here we explore two main explanations for the lack of policies aimed at LR breeding, both of which have links to knowledge and politics. One explanation may be that current scientific knowledge is not conclusive about breeding being sufficiently effective to improve LR resistance significantly. In that case, there would be little need to introduce policy instruments to stimulate breeding for LR.

An alternative explanation is that there is a gap between policy measures and the current state of knowledge*:* there is available and agreed with scientific information indicating that specific policy instruments should have been introduced, but for various reasons, this has not been done. Andresen and colleagues (2018) suggest that such regulatory gaps may be explained by conflicting interests, state of saliency, and organizational factors. First, opposition from commercial interests may impede the development of environmental policy instruments by reducing the influence of scientific knowledge. Second, while public demand for regulation of environmental challenges may enhance regulatory action, high saliency could tend to increase polarization and reduce the impact of science. Third, the organizational explanation assumes that there may be a gap between management and knowledge production due to fragmented and complex organizations. The background for these four explanatory assumptions is further explored here and then summed up in Table 1.

Our first explanatory variable concerns the state of knowledge. A central tenet in science–policy analysis is that the more consensual the state of scientific advice, the more likely is it to be used as decision-making premise for management, whereas scientific uncertainty and disagreement reduce the chances of scientific advice to influence decision-making (Underdal, 2000). Our point of departure is Norway's firm political commitment to knowledge-based management, and the growing body of knowledge concerning ecosystem management (White Paper, 2014–2015; White Paper, 2013). We examine how scientific knowledge has been applied in devising Norway's range of licences and its TLS, both of which are targeted at reducing the sea lice problem. There might be a lack of scientific agreement that LR breeding is a viable option to reduce the lice problem in salmon aquaculture. Here we rely partly on results from responses from breeders and farmers (Rosendal & Olesen, 2022). To this, we add responses from interest groups (NGOs) and public authorities about how they perceive the scope for breeding for LR in salmon, and whether they have attempted to influence breeding strategies relating to LR. Against this backdrop, our point of departure is as follows:

> Assumption 0: Policy instruments have not been aimed at LR breeding, due to scientific uncertainty as to whether LR salmon would contribute sufficiently to resolve the lice problem.

Alternatively, there may be a gap between scientific advice (knowledge) and policies. Drawing on Andresen and colleagues (2018) we examine two factors that could account for this discrepancy: interests and organization.

We start by investigating the level of conflicting interests. The management and regulation of environmental challenges and technologies do not necessarily conform strictly to the production of scientific knowledge. There is general agreement in the science-policy literature that political conflicts of interest may negatively affect the influence of science (Miles *et al*., 2002; Underdal, 2000). If different types of advice are provided, then politically and economically stronger actors may be expected to prevail as regards the type of scientific advice to be used (Underdal, 2000). Here we need to examine the policy dialogues between government bodies and stakeholders, including commercial actors. We narrow in on the interests and preferences of non-state actors who have a commercial interest in breeding and would be affected by regulation. We expect that the higher the conflict of interest, the less likely is scientific advice to be used as a decision-making premise for policy instruments, and vice versa. This leads to our first alternative explanation:

> Assumption 1: Policy instruments have not been aimed at LR breeding, due to high levels of conflicting interests which reduce the impact of science on politics.

A related interest-based explanation here is that there have been few advocates of LR breeding among environmental proponents. Typically, the drive for enhanced or stricter environmental politics is fronted by public agencies or non-state actors representing environmental interests. As discussed by Underdal (2000), in issue-areas with high levels of conflicting interests, high public salience may lead to increased polarization and reduce the impact of scientific knowledge on decision making. The converse may be true for problems with low levels of conflict, where public salience will tend to increase scientific influence (Andresen *et al*., 2018). This leads to our second alternative assumption:

> Assumption 2: Policy instruments have not been aimed at LR breeding, because of high salience among environmental proponents (which reduces the impact of science on politics).

Finally, the lack of policy instruments designed to enhance LR breeding could be due to complexity and fragmentation in relevant decision-making processes. This explanation assumes that the gap between scientific knowledge and policy instruments is caused by organizational fragmentation or complexity at the national level. Essentially, 'fragmentation' refers to the distribution of competences among and between governmental agencies (Biermann *et al*., 2009). Different regulatory actors may perceive problems differently and apply different decision-making criteria, as captured by Allison's 'where you stand depends on where you sit' (Allison, 1971). Against this backdrop, we can add another assumption:

> Assumption 3: Policy instruments have not been directed at LR breeding, because high levels of complexity and fragmentation between government agencies reduce the influence of science on policy instruments.

Table 1: Summary of assumptions: how the state of scientific knowledge may affect the choice of developing policy instruments to stimulate LR breeding

A0: Scientific discord on LR, hence	no policy incentives for LR breeding
A1: Scientific agreement on LR, but	…high conflict of interests reduces impact of science on policy = no policy incentives for LR breeding
A2: Scientific agreement on LR, but	…high saliency reduces impact of science on policy = no policy incentives for LR breeding
A3: Scientific agreement on LR, but	…administrative complexity reduces impact of science = no policy incentives for LR breeding

2.2 Methodology

We applied an interdisciplinary approach of political science and aquaculture genetics, also described and applied earlier (e.g. Olesen *et al*. 2007; 2015; Rosendal *et al*. 2006; 2013). The social science element involved identifying cognitive, social, institutional, and legislative aspects governing aquaculture, and then examining how these factors might affect the development of policy instruments. Insights from the life sciences (aquaculture genetics) were applied to investigate and interpret scientific knowledge on which current policy instruments are based, as well as for understanding the effects of policies on fish welfare, growth performance, sea lice occurrence, breeding, and commercial benefits. Our methodology for collecting empirical data material here drew on relevant policy documents, white papers, and academic literature covering disciplines from parasitology, immunology, and genetics to legal and political science.

Another major source of material came from interviews with key actors in governing institutions and with environmental NGOs. Here we conducted in-depth interviews with 11 key experts from the Norwegian Food Safety Authorities, GenØk (currently NORCE), the Norwegian Directorate of Fisheries, the Ministry of Trade, Industry, and Fisheries, and four representatives from the NGO sector (WWF, Bellona, the GMO Alliance, and Dyrevernalliansen (the Animal Welfare Alliance). We have also included a data from our previous study (Rosendal & Olesen, 2022), where we interviewed a representative selection from the salmon farming industry and all the four corporations involved in salmon breeding in Norway as well as 4 salmon producers. Given the sensitivity of the issue, and as requested by our respondents, we have made the list of interviewees confidential.

The interview method was based on open and non-standardized questions to key actors (see Annex 1 for the guide to open questions). Our aim was to explore the nuances in views and perceptions concerning breeding for sea lice resistance in farmed salmon. With this purpose in mind, we chose a broad range of interviewees from a representative selection of stakeholder groups. In contrast to a statistical survey, we did not set out to quantify how many respondents hold a particular opinion. We rather aimed to ascertain that a broad selection of perceptions was brought into our presentation and discussion of the topic. Our in-depth and explorative interviews are well suited to the case study (Yin, 2003). This type of study is likely to expose intrinsic characteristics with a low scope for generalising to other countries.

As this was a multidisciplinary study engaging in interviews, we paid extra attention to the validity and clarity of central concepts in the issue area. The interpretation of how legal, institutional, and biological factors affect the state of breeding for lice resistance in the salmon farming sector is expected to be enhanced by combining insights from political science and genetics.

3. Breeders and the state of LR breeding

3.1 Structures and actors involved in LR breeding

The structure of the Norwegian salmon breeding programmes has changed significantly in recent decades (Olesen *et al.*, 2007; Rosendal *et al.*, 2013; Rosendal & Olesen, 2022). Public breeding programmes for salmon and rainbow trout (*Oncorhynchus mykiss*) were launched in 1971 (Gjøen & Bentsen, 1997). After a period of cooperative organization, the breeding programme was taken over by a new Norwegian shareholder company, AquaGen, in 1993 (Gjedrem, 2010;) where the government became a majority owner and could have an impact on breeding strategies. In 2013, the remaining public shares were sold to the German-based EW Group – a multinational, world-leading breeding corporation for poultry, pig, and aquaculture. In 2014/15, SalmoBreed and Akvaforsk Genetics Center (also with majority government ownership) were sold to (UK) Benchmark Holdings, a multinational investment corporation.

Today, the two major breeding companies marketing salmon roe in Norway are Benchmark Genetics (SalmoBreed and Stofnfiskur breeding programmes) and EW Group (AquaGen breeding programme). Another two breeding programmes are integrated as parts of the (Norwegian) multinational corporation Mowi and the smaller (but still second-biggest Atlantic salmon producer worldwide) Norwegian corporation, SalMar. By 2015, Norway's four breeding programmes for salmon had been entirely transferred from domestic/public to foreign/private control and management, in turn enhancing the technological and economic strength of the commercial actors in the salmon farming sector. The sector has strong economic muscle and may exert considerable influence by contributing to local employment, investments and innovation.

3.2. The state of breeding for LR: enhanced agreement

Gjerde (2013; 2018a; 2018b) predicted a 75% reduction in lice per fish after five generations of family selection for LR only (based on significant heritability estimates). Supporting these findings, Tsai and colleagues (2016) showed how host resistance to sea lice in farmed Atlantic salmon has a significant genetic component, and concluded that, 'given the high economic importance of resistance to sea lice, and the efficacy of genomic prediction, it is likely that selective breeding for this trait using genomic data will become an important component of sea lice control' (Tsai *et al*., 2016). There has been a debate between a scientist in aquaculture genetics (Professor Bjarne Gjerde, Nofima and Norwegian University of Life Sciences) and a scientist in fish health and pathology (Professor Frank Nilsen, Director of the Sea Lice Research

Centre at the University of Bergen) regarding the long-term impacts of genetic LR. Here, the risk of co-evolution towards more aggressive sea lice (resulting from LR salmon) has been highlighted by the latter researcher (Gjerde, 2018a; 2018b). However, risk of co-evolution has not been voiced as a criticism when gene-editing technologies are applied to breeding for lice resistance. This could indicate a shift towards increased scientific agreement about the potential and benefits of genetic improvement for LR.

AquaGen reported up to 60% reduction in lice infestation after only two generations when the breeding objective focused solely on LR (Jensen, 2018). SalmoBreed (currently Benchmark Genetics) reported a 10% reduction in lice infestation after two and a half generations of selection for an aggregate breeding goal, including LR as one of the target traits (Hillestad *et al*., 2017). The genetic gain for each trait is expected to decrease when more independent and equally important traits are added into the breeding goal (Hazel & Lush, 1943). Hence, these results are consistent and show the difference between selecting for LR only (rapid genetic gain in LR) and adding LR to the aggregate breeding goal, including several traits (slow genetic gain in LR). The former strategy is costly in terms of loss in further gains from conventional breeding goals for faster-growing salmon, while the latter is costly in terms of delays in reaching LR goals to improve fish welfare while reducing the impact of salmon lice on wild salmon (Rosendal & Olesen, 2022). Selection for more traits may result in a lower selection differential than for one or two traits, but the total effect may cause a greater economic gain. Anyhow, broad breeding goals combining production and welfare traits are standard in animal breeding programmes and result in improvement in economically important traits while maintaining genetic variation for potential new traits to be included in future breeding goals. This is also demonstrated by the 10% gain obtained for LR in addition to faster growth by SalmoBreed.

Recently, the validity of current lice challenge tests used for selection of LR has been questioned. Results of Ødegård and colleagues (2022) indicated that expected genetic gain in LR based on current communal challenge testing of families with different LR potential may not be realized when only salmon with similar LR status are stocked together in the same cages. Results from other ongoing projects on LR (e.g., NOlice - Novel tools and knowledge for a future with no lice infestations in Norwegian aquaculture, Research Council of Norway Project no. 320619; GeneTReat - Economic impact of genomic selection on reducing treatments for sea lice infestation in Atlantic salmon aquaculture, Research Council of Norway Project no. 332349) and future research might further illuminate these issues. Hence, more efficient designs of challenge traits might be required for successful LR breeding.

With a partly albeit not considerably more LR fish (requiring fewer delousing treatments), selective breeding for LR might still be effective – if all or almost all farms opted for the resistant fish. However, as one farmer's or breeder's loss may be another's gain – leading to 'free rider' situations – this type of innovation is unlikely to be stimulated by market-based factors (Rosendal & Olesen, 2022): The farmer who chooses LR material will contribute to the common good by reducing the overall lice infestations in the area but will have to bear the costs of using slower-growing fish. Meanwhile, neighbouring farmers may remain 'free riders', benefitting from less lice infestations and still using fast-growing fish themselves.

4. Discussion: what explains lack of policy instruments aimed at LR breeding?

4.1 Science and politics

We start with the cognitive dimension – the state of knowledge concerning whether more intensive breeding for LR fish could contribute sufficiently to solving the sea lice problem in aquaculture. Our findings indicate that there is currently a high level of scientific agreement about the significance of the sea lice problem, and that LR breeding is an efficient approach for combatting salmon lice in salmon farming (Rosendal & Olesen, 2022; Gjerde, 2018a; 2018b; Tsai *et al*., 2016). Further, we have established that no policy instruments have been specifically aimed at stimulating breeding for LR, despite strong indications that this can be successful. Research shows promising results for achieving LR in salmon – granted that this constitutes a significant focus in the breeding programme.

There is, however, a short-term economic downside. A significant focus on LR would imply economic losses in the short-term gain in e.g., growth rate, as selection pressure for other traits would be weakened. The loss in the genetic gain in other economically important traits is a likely reason why market actors have not opted for a greater focus on selective breeding for LR to obtain almost-resistant fish. In addition, the accompanying reduced gain in growth would mean that the fish would need a longer growth-period in the sea, compared to fish selected for even faster growth. This might exacerbate the lice challenge and further explain why breeders have not chosen significant selective breeding for LR (to the extent required to reduce the number of treatments) That could explain the lack of market-based demand for LR fish – but not the lack of policy incentives.

The relationship between delousing treatments and heart failure also warrants additional comments. Exploiting the advantages of having faster-growing fish (with the same lice-levels and LR) by stocking more fish per year in the sea, the potential number of salmon lice affecting wild salmon will not be reduced and would mean treating more fish against lice although each fish might need to undergo fewer treatments. Additionally, the 'fast-growth strategy' of including rapidly growing fish during intensive smolt production has several disadvantages (Frisk *et al*. 2020). Intensive smolt production with high temperature and faster growth has been shown to be associated with slow growth at sea and cardiac morphological alterations, several of which were associated with increased mortality (cardiac rupture) after mechanical delousing during a CMS outbreak. Further, there are numerous reports of undesirable (cor)related effects of selection for high production efficiency (e.g., faster growth), concerning metabolic, reproduction and health traits, in broilers, pigs and dairy cattle (see, e.g., Rauw *et al*., 1998). This is explained by the 'resource allocation theory' presented by Beilhartz and colleagues (1993); it implies that focusing on faster growth rates may compromise other critical physiological characteristics and health traits of farmed salmon. Regardless, the added negative impacts on fish health from steadily increasing delousing treatments remain the same.

As all this indicates a rather low level of scientific uncertainty, we need to examine other factors than scientific knowledge to account for the state of breeding for LR gap. First, let us consider the policy instruments applied to stimulate sustainable innovation in aquaculture.

Among the most central policy instruments, the TLS was designed especially for dealing with the lice problem, aimed at reducing infestations spreading to wild fish and at ensuring predictable and sustainable growth in production (Fauchald, 2020). TLS is only partly designed as an environmental instrument and has been criticized by NGOs for targeting solely sea lice (Fauchald, 2020). The system is intended to be developed continuously, on the basis of available and best scientific knowledge. The TLS 'colours' are assigned according to the predicted effects of sea lice on wild salmon, in turn determining whether farmers are allowed to continue expanding, maintaining or must reduce their salmon production in a given production area. In 2020, nine production areas were accorded the green light, which allowed them a production increase of 6%; two areas got the yellow light (no change in production) whereas two areas received a red light, entailing 6% reduced production capacity. Farmers that comply with certain exemption criteria (low levels of lice below 0.5 adult female lice per fish over time) were offered as much as 6% production capacity increase at specific locations, independently of the colour received. This constitutes a strong driver for greater use of delousing treatments, as producers will wish to increase their production.

The main goal of the TLS is to increase sustainable salmon production – and this will require solving (or at least significantly reducing) the lice problem. Salmon farmers align with the Norwegian government in wanting to resolve the lice problem, as this is the major hindrance to increasing production. However, as long as breeding does not result in high levels of lice-resistant fish, breeding for LR will not receive any incentives from the TLS.

This overall science-policy agreement gives rise to the question of why none of the licence applications and grants (Development, Research, 'Green' and Brood Stock licences) have been aimed at stimulating LR breeding (Larsen & Vormedal, 2021; Greaker *et al*., 2020). The licences are described as very low-cost policy instruments, which are highly valuable for the breeders and farmers. Compared to the 13 production areas that constitute Norwegian salmon farming, the sum of these licences ranks 7th in terms of number of location areas with such licences, and as 12th in terms of tons of fish produced by these licenses – which clearly indicates their significant value (see Appendix 1). Salmon breeders (and multipliers) can apply for brood stock licences (without specific application deadlines and no limit on number of licences applied for) to obtain extra production of grow-out and broodfish candidates. A description of the breeding activities is requested, including objectives for systematic breeding in the breeding nucleus population (e.g., increased growth rate and disease resistance). Further, for multipliers of improved salmon roe, specification of the breeding lines (e.g., efficient, or robust elite roe) used can be provided. Nevertheless, no brood stock licences have been applied to stimulate or request LR breeding to reduce the sea lice challenges (Larsen & Vormedal, 2021; Greaker *et al*., 2020).

The licences allow for increased salmon production in a situation where production is otherwise at a standstill (Vormedal & Gulbrandsen, 2018; Greaker *et al*., 2020). These licences could have been applied as policy instruments for directing or stimulating breeding in a desirable direction to enhance environment and fish health and welfare.

Given the high level of scientific agreement on LR breeding and the lack of policy instruments aimed at promoting this, we ask whether our alternative explanatory factors might account for the lack of policy incentives for LR breeding.

4.2 Interest-based explanations

The conflicting interests-perspective gives rise to an alternative explanation of the regulatory situation. Here, the point of departure is that Norwegian aquaculture is often portrayed as a sector where corporate interests are successful in lobbying political decision-making processes (Aarset & Jakobsen, 2015; Fauchald, 2020) while also subject to strong lobbying from environmental NGOs. In the face of high conflict levels, this perspective explains policy measures as a result of powerful interests, rather than being knowledge-based and resulting from scientific advice. We have noted the high level of agreement between decision-makers and industry actors as to increasing the production of salmon – and, following that, an agreed interest in solving the lice problem as a precondition for increased production, as lice are perceived as the major bottleneck.

The interest-based perspective might also predict a high level of compliance with the resulting policy measures – but that would be due to dominating interests winning through, rather than due to scientific agreement. Viewed from an interest-based explanatory perspective, the TLS and the various types of licences are the result of aggregate interests (domestic politics) where corporate actors have had a breakthrough for their interests, partly because of economic muscle and partly as they act together as a well-organized coalition. Due to the Broodfish and other licences, the breeding companies also have significant incomes from producing salmon (see Appendix 1). As the licences come with no strings attached as regards breeding, salmon industry actors have been offered no incentives to adapt their breeding strategies.

Nevertheless, Rosendal and Olesen (2022) found agreement among farmers and breeders that direct stimuli by policy incentives might have been effective in promoting a stronger focus on LR breeding in breeding corporations. Some breeding corporations pointed out that political interest in this direction could have been helpful vis-à-vis their internal boards in arguing for a stronger emphasis on LR breeding. Why, then, has the aquaculture industry not lobbied for incentives to enhance breeding for LR? Rosendal and Olesen (2022) note a mixed bag of explanations here:

First, the breeding corporations mentioned 'regulatory fatigue' which kept them from lobbying for more interference from politicians. Second, the corporations explained their inaction as a general reluctance to cooperate on lobbying at the national level – due to high internal competition. Third, the two major breeding corporations (EW Group and Benchmark) are externally based; compared to the farmers and farmer organizations, they might be unfamiliar with the lobbying culture within the Norwegian aquaculture sector. The breeding corporations do cooperate on lobbying together with other farm animal breeders, but only at the European level, where the aim is to relax current regulations on gene editing technology.

Finally, fish farmers still demand fast-growing salmon, in order to shorten the sea-rearing period that exposes the fish to salmon lice, and lower production costs. Consequently, the breeders also want to maintain the selection pressure on growth rate, which limits the scope for putting much greater emphasis on LR (Rosendal & Olesen, 2022). Faster-growing fish may make it possible to reduce the number of treatments per fish before harvesting, but the average number of lice per fish is not reduced. Further, with faster-growing fish, more fish can be stocked in the sea within the same maximum biomass of the license. By implication, the number of fish being stocked per license might increase, but the average number of lice per fish would not necessarily decrease. In effect, the total number of lice in the sea might increase, increasing the number of lice that might be transferred to wild salmon.

These lines of explanation are all connected to why salmon breeders and farmers have not lobbied for policy instruments to support LR fish, or indeed utilized the licences to promote this type of breeding. However, this cannot explain why the governing authorities have not applied incentives to stimulate breeding for LR. For instance, the fisheries authorities could have achieved this by more active use of the broodstock licences, or any of the other licences. Might there be interest-based reasons for this regulatory reluctance on the part of the Norwegian government?

It is possible that the authorities refrained from interfering because they perceived (and made allowance for) strong resistance among the multinational corporations involved. From our key actor interviews, there seems to be broad political and corporate consensus that the government should not intervene in the internal breeding strategies of the corporations. It is hardly surprising to find this sentiment among corporate actors, but it seems less intuitive that the political and administrative sectors should agree. Even right-wing and conservative parties in Norway have traditionally acknowledged the need to regulate market actors, particularly to protect environmental and animal interests, albeit to a lesser extent than more socialist-oriented and 'green' parties. The eight years (2013–2021) with a conservative government might hence account for some of the situation. This line of explanation is supported by our interviews: under the conservative government and then following the completion of the restructuring of the aquaculture sector in 2015, there has been growing political agreement that fish breeding is not and should not be a public concern. A prevailing view among our respondents is that the politicians in charge concurred that the government should not interfere in breeding goals in aquaculture.

While the lack of policy instruments to support LR in breeding may be due to political factors, there is still a great deal of dissatisfaction with the situation among administrative bodies. We encountered frustrations among government agencies with what they perceived as the dearth of policy instruments to steer and strengthen problem-solving to combat the lice problem. Thus, the interest-based perspective cannot fully explain the persistent administrative and political inaction concerning breeding goals. How may public salience help to explain the regulatory situation? Here we draw on interviews with environmental proponents (NGOs) on their views on how to deal with the lice problem.

4.3 Salience, and lack of public demand for LR breeding

Here we assumed that high salience could increase conflict levels and in turn reduce the impact of science on policy-making.

Environmental problems in the aquaculture sector receive considerable attention from NGOs – but there is also a divide between those attentive to habitats and wildlife, and those focused on animal welfare issues, including the welfare of domesticated animals. These concerns do not always pull in the same direction, as the focus on reducing the sea lice pressure on wild salmon may partly run counter to concerns for animal welfare in farmed fish.

Most of the NGOs criticism of the regulatory system (especially of the TLS) has concerned the policy objective of increasing open-cage production in the fjords. Wildlife-oriented NGOs aim for downscaling of aquaculture, which may have lessened their interest in and attention to tackling the lice problem with current or increased production levels. These NGOs argue that several other environmental problems besides lice will need to be resolved for salmon farming to become sustainable – and that may have reduced their attention to resolving the lice problem by means of breeding.

Less critical or more willing to compromise on aquaculture practices is the WWF, which has supported labelling of aquaculture products by the Aquaculture Stewardship Council (ASC). ASC labelling is a private-sector tool – which, however, compared to other salmon markets, has not been prevalent in the Norwegian aquaculture sector (Vormedal & Gulbrandsen, 2018). Regarding fish diseases, all ASC-certified salmon farms are required to adhere to rigorous requirements to minimize disease outbreaks. Fish farms must show low levels of parasites (especially sea lice) and are permitted to use medicine only after a disease has been diagnosed: prophylactic use is prohibited since the start of the certification in 2012. However, preventing high sea lice counts by using genetic LR seed is still not a requirement or recommendation for ASC certification, or for organic certification.

Why, then, have the wildlife-oriented NGOs not been more attentive to the potential of breeding techniques and results? One possible answer could be connected to the gene-editing debate, which also concerns breeding techniques. Controversies regarding possible changes in gene-technology regulation involve several suggested changes in the Norwegian Gene Technology Act (GTA), in response to new gene-editing technologies (e.g. CRISPR) and the possible implications for patent protection (intellectual property rights). In the GTA hearings, six environmental NGOs were critical to a liberalization of the Act (Genteknologiutvalget, 2021). One interviewee indicated that the environmental NGOs' critical attitude to GMOs, including modern CRISPR products, may explain their reluctance to embrace and support all technologies concerning genetic improvements, including traditional selective breeding. This could help to explain the scant NGOs attention to the potential for LR breeding. However, other NGOs interviewees did not support this interpretation.

The animal welfare NGOs seem to have a stronger focus on breeding strategies as part of solving the environmental challenges in aquaculture. Noting the long and successful tradition whereby the public authorities have focused on sustainable agriculture, interviewees indicated that this ought to be the objective also for aquaculture management. Further, it was pointed out that the Animal Welfare Act endows the authorities with scope for setting requirements on breeding strategies, including fish breeding and foreign breeding corporations. Similarly, Dyrevernalliansen has requested that mortality be included in the TLS, to reduce fish mortality connected to delousing treatments.

Another explanation mentioned by several interviewees was that LR and breeding go under the radar of the NGOs and the public at large, as indicated by the way the topic is treated in the media. Sea lice infestations and other environmental problems related to farmed salmon are recurring topics in the media and, coupled with general attention to aquaculture as a significant economic sector, public salience is high. Otherwise, however, there is little media attention related to breeding, except for the regulation on gene editing and the GMO debate, mentioned above. A similar lack of attention might well be the case for politicians and governing bodies.

However, this lack of attention to breeding has not always been so: selective breeding is the major reason for the success of Norwegian farmed salmon (Gjedrem & Baranski, 2009). When the Norwegian salmon breeding programmes were publicly owned or handled by cooperatives with public shareholders, the authorities could influence breeding goals; moreover, the programmes usually included broad breeding goals (Rosendal *et al.*, 2013). Today, all breeding programmes have been privatized, and the government is either excluded or has itself refrained from interfering in breeding strategies. Across the board, the NGOs emphasized the need for the government to strengthen its demands on the aquaculture sector.

Although it is reported that Norwegian households were willing to pay a significant extra tax of approximately 100 EUR (1 034 NOK) per year to support breeding for LR-resistant salmon (Grimsrud *et al*., 2013), the government has not been subjected to public demands for support to LR breeding. Breeding for LR has not figured on the agenda in newspapers, among the general public, or NGOs.

In sum, these factors may help to explain the lack of attention. The high level of salience has focused on reducing production in open cages, not on ameliorating breeding or production strategies other than closed systems (or sterile salmon). However, the absence of public demand cannot explain the lack of policy measures, given the government's explicit aim of knowledge-based management. What, then, of the management segment?

4.4 Complexity and fragmentation in regulating aquaculture

Beside the two interest-based explanations, we assumed that having a fragmented administration with a complex division or organization of responsibilities could reduce the role and influence of scientific knowledge on policymaking. Aquaculture is subject to considerable regulation in Norway – from the municipal, county, and national levels. Further, aquaculture management is highly fragmented, with responsibilities shared between the animal health and welfare, food, environmental and trade-related authorities (Solås *et al*., 2015).

The fisheries authorities have overall responsibility for aquaculture management: it is the Ministry of Trade, Industry, and Fisheries (NFD) that sets the rules for aquaculture. The Directorate of Fisheries coordinates policies and cooperates with the municipalities, the counties, and the environmental sections of the County Governor, the Norwegian Coastal Administration, and the Norwegian Food Safety Authority (FSA). Fish health and welfare is the responsibility of the latter.

Some have argued that environmental concerns have taken precedence over economic and social concerns in aquaculture management (Solås *et al*., 2015). Others find indications that trade, and economic interests (the Ministry of Industry, Trade and Fisheries – NFD) may have dominated over health (the Food Safety Authorities – FSA) and environmental (Ministry of Climate and Environment – MCE) concerns (Fauchald, 2020). The various parts of the administration acknowledge the central role of the NFD, which is in charge of aquaculture management and commands the general policy instruments. We can note a perception among some of the administrative bodies that they find it difficult to have any impact on aquaculture policy goals. For instance, the FSA lacks the overall policy instruments to deal with high mortalities ('documenting massive fish deaths') resulting from the increasing number of delousing treatments. The FSA is responsible for the symptoms but lacks the direct means to do anything about the root causes: all it can do is react on a case-by-case basis. The design of the TLS allows only one medicinal delousing treatment – but does not set any limits on the frequency/number of other types of delousing treatments, such as mechanical treatments. High and increasing mortalities are associated with increased frequency of mechanical delousing treatments (as documented by the Veterinary Institute reports: Hjeltnes *et al.,* 2019; Sommerseth *et al.,* 2022), recognized as a major problem by the FSA.

A policy strategy aimed at reducing the number of delousing treatments, including mechanical ones, would be preferable to the FSA. Hence, the FSA might welcome more LR fish populations, as this could help to reduce the number of delousing treatments, which affect fish health negatively. One of the few policy tools available to FSA is the administrative order on aquaculture zones. This could have been applied to perform validation or demonstration cases designed to compare zones with and without high levels of LR in fish. Such demonstration cases could involve testing of more genetically lice-resistant material in various zones, so that the market could be better informed about the potentially positive effects of LR breeding on the number of treatments against sea lice. A favourable outcome here could stimulate the demand from farmers and further persuade the breeders to emphasize this trait in their breeding goals.

As also pointed out by environmental NGOs, a central constraint for other actors to influence policy-making lies not so much the administrative fragmentation, but in the close relationship between the ministry in charge (NFD) and the aquaculture industry. The two ministries responsible for environment and animal welfare remain subordinate to the NFD, which (according to a broad range of interviewees) is sensitive to the interests of the salmon industry. It is an open question whether the recent shift in government is likely to change this situation. A conservative government is commonly more responsive to industry needs, but the new 'red-green' governing parties have their electorate roots firmly linked to 'growth and employment' (Labour Party) and to the food-producing sectors (the Centre Party, which emanates from the earlier Farmers' Party).

However, the emphasis on animal welfare might strike a new chord. In its latest annual report, the Veterinary Institute (Sommerseth *et al*., 2022) calls for improvements of the regulatory framework – for example, through active enforcement of implementation of the Animal Welfare Act in other regulations. Further, the establishment of systems for rewarding actors who emphasize fish welfare has been requested by the Veterinary Institute (Sommerseth *et al*., 2022). Following the reports from the Veterinary Institute on the links between delousing and fish welfare problems, there has come a growing multi-sector demand that limits on mortality should be included in the TLS. The FSA has repeatedly made this call (Nedrejord, 2022), which has recently also been made by the Deputy Minister of the NFD.

All this weakens our assumption that administrative fragmentation may directly explain the lack of policy instruments aimed at stimulating LR breeding. A more plausible explanation may lie in the close relations between the ministry in charge and the aquaculture industry – which brings us back to the discussion of interests. When industry interests and political interests concur, there is less scope for knowledge-based management and hence less scope for administrative bodies to affect aquaculture policy instruments. Indirectly, however, complexity and fragmentation in management might tend to obscure decision-making and allow for the development of close relations between the interests of industry and the authorities.

5. Summing up and concluding remarks

This study from Norway has investigated how the absence of policy instruments directed at stimulating LR breeding might be explained. We found a quite high level of scientific agreement that LR breeding could be a viable option for reducing the sea lice problem. More intensive selective breeding for LR could lessen the number of delousing treatments and enhance survival and welfare among both wild and domesticated fish, seen as broadly corresponding with current perceptions.

The absence of economic, market-based incentives to promote this strategy among breeders and farmers has already been documented (Rosendal & Olesen, 2022). Hence, applying gene-editing breeding strategies for resistance to CMS may be more appealing to the breeding companies than tackling the polygenic (and not patentable genes of) LR traits. In any case, these strategies hinge on technological and legal developments (Rosendal & Olesen, 2022). Furthermore, it can be seen as a choice between 1) targeting the root causes of cardiac health and mortality problems (by reducing stress of lice treatments through LR salmon and (or) reducing intensity and growth rate of smolt production to improve cardiac health and prevent CMS) and 2) target the symptoms of the cardiac health problems (without reducing stress and the poorer cardiac performance), by editing CMS gene(s).

The aquaculture sector is characterized by strong commercial interests, which, according to our analytical assumptions, may lessen the influence of science in political decision-making. Without market-based incentives for stronger selective breeding for LR (patents do not apply; free-rider problems dominate), the private sector is unlikely to choose LR unless there are political incentives.

Aquaculture production is a highly salient issue among NGOs and the public in general but no calls for LR breeding have come from these actors. Wildlife-oriented NGOs outnumber the animal welfare NGOs; and attention has focused on reducing production, particularly in open cages, rather than on improving salmon production through selective breeding strategies. Breeding seems to go unnoticed by the public at large and receives scant media attention. Our analytical approach to salience may have underestimated the complexity of the environmental challenges associated with the aquaculture sector and put too much weight on polarization. In contrast to short-term mechanical solutions to reduce the lice problems for farmed or wild salmon, LR breeding requires a long-term perspective to solve the salmon sea lice problem. This could constitute a more likely explanation for the lack of public demand for policy instruments aimed at LR breeding than high salience and polarization.

Finally, we investigated why fisheries authorities have not put stricter requirements upon the salmon farming and breeding industry to produce and deliver salmon roe with higher LR. After all, the policy measures for environmentally friendly aquaculture applied so far consist of substantial monetary incentives (see Annex 2). These policy instruments might have been employed to enhance breeding in addition to (or instead of) the highly spectacular offshore and on-land mechanical installations. Here also, the consensus between regulator and regulated farmers concerning problem description and policy measures seems high.

We asked whether a fragmented administration, with a wide range of governmental agencies and sectors involved and partly responsible for sea lice management, might have reduced the influence of science in policymaking. Our interviewees indicate that administrative fragmentation is a problem subordinate to that of the close ties between political and industry interests. Encouraging selective breeding for LR is not the preferred choice as seen from an interest-based perspective and could explain why such incentives are not the preferred solution of the politicians in charge. This strengthens our assumption that strong economic interests may reduce the role of science and knowledge-based management, in turn explaining the dearth of policy instruments aimed at stimulating LR breeding.

Suitable policy instruments could include requests or incentives for emphasizing LR more in the breeding goal of the breeding nucleus. Broodstock licences could also include specific criteria for defining elite roe – e.g., from broodstock with high estimated breeding value (say min 1 genetic standard deviation) for LR – used by multipliers. Alternatively, a tax deduction or increased production quota (e.g. additional licences) could be allocated to farmers of lice-resistant salmon to spur the demand for LR roe. Political willingness to regulate or stimulate the breeding strategies of private actors seems lacking. However, as we have shown, the overall policy goal of knowledge-based management would seem to increase the rationale for applying such policy incentives.

References

Aarset, B. and Jakobsen, S.E. 2015. Path dependency, institutionalization, and co-evolution: The missing diffusion of the blue revolution in Norwegian aquaculture. *Journal of Rural Studies*, 41, 37–46.

Allison, G. 1971. Essence of Decision: Explaining the Cuban Missile Crisis. Little, Brown and Company, Boston. 338 pp.

Andresen, S., Skodvin, T., Underdal, A., Wettestad, J. 2000. Science and politics in international environmental regimes. Manchester: Manchester University Press. 221 pp.

Andresen, S.G. Rosendal, K. Skjærseth, J.B. 2018. Regulating the invisible: interaction between the EU and Norway in managing nano-risks. *International Environmental Agreements: Politics, Law and Economics*, online 21.05.2018, 16 pp.

Bechmann, R.K., Arnberg, M., Gomiero, A., Westerlund, S., Lyng, E., Berry, M., Agustsson, T., Jager, T., Burridge, L.E., 2019. Gill damage and delayed mortality of Northern shrimp (*Pandalus borealis*) after short time exposure to anti-parasitic veterinary medicine containing hydrogen peroxide. *Ecotoxicology and Environmental Safety*, 180, 473–482.

Beilharz, R.G., Luxford, B.G., Wilkinson, J.L. 1993. Quantitative genetics and evolution: Is our understanding of genetics sufficient to explain evolution? *Journal of Animal Breeding and Genetics*, 110, 161-70.

Biermann, F., Pattberg, P., van Asselt, H., Zelli, F. 2009 'The Fragmentation of Global Governance Architectures: A Framework for Analysis', *Global Environmental Politics*, 9, 14–40.

Boison, S., Ding, J., Leder, E., Gjerde, B., Bergtun, P.H., Norris, A., Baranski, M., Robinson, N. 2019. QTLs associated with resistance to cardiomyopathy syndrome in Atlantic salmon. *Journal of Heredity*, 110, 727–737.

Fauchald, O.K. 2020. Miljøprinsipper og strategiske beslutninger – reform av norsk lakseoppdrett ('Environmental principles and strategic decisions - reform of Norwegian salmon breeding') *Tidsskrift for rettsvitenskap*, Vol 154, Nos 2–3, 264–305. In Norwegian.

Frisk, M. Høyland, M., Zhang, L., Vindas, M.A.. Øverli, Ø., Johansen, I.B. 2020. Intensive smolt production is associated with deviating cardiac morphology in Atlantic salmon (*Salmo salar* L.). *Aquaculture*, 529, 735615.

Genteknologiutvaget. 2021. Genteknologiutvalget. Se innspill – Genteknologiutvalget. Accessed 30.05.2023.

Gjedrem, T. 2010. The first family-based breeding program in aquaculture. *Reviews in Aquaculture*, 2, 2-15.

Gjedrem, T. and Baranski, M. 2010. Selective breeding in Aquaculture: An Introduction. Springer Dordrecht. 221 pp.

Gjerde, B. 2013. Mot utval for auka motstandskraft mot lus hos laks. Fakta-ark. Nofima rapportserie. 11 pp. In Norwegian (English summary). https://nofima.brage.unit.no/nofima-xmlui/handle/11250/284250.

Gjerde, B. 2018a. Kan vi på sikt sleppe å sette inn tiltak mot lus? Norsk Fiskeoppdrett (2018), p. 6. In Norwegian.

Gjerde, B. 2018b. Er avl mot lus eit sisyfosarbeid?, Norsk Fiskeoppdrett, Vol. 43, No. 8, 90. In Norwegian.

Gjoen, H. and Bentsen, H.B. 1997. Past, present, and future of genetic improvement in salmon aquaculture. *ICES Journal of Marine Sciences*, 54, 1009–1014.

Greaker, M., Vormedal, I., Rosendal, K. 2020. Environmental policy and innovation in Norwegian fish farming: Resolving the sea lice problem? *Marine Policy*, 117, 1–10.

Grimsrud, K., Nielsen, H.M., Navrud, S., Olesen, I. 2013. Households' willingness-to-pay for improved fish welfare in breeding programs for farmed Atlantic salmon. *Aquaculture*, 372–375, 19–27.

Hazel, L.N. and Lush, J.L. 1943. The efficiency of three methods of selection. *Journal of Heredity*, 33, 393–399.

Hillestad, B., Moghadam, H.K. 2019. Genome-wide association study of Piscine myocarditis virus (PMCV) resistance in Atlantic salmon (*Salmo salar*). *Journal of Heredity,* 110, 720–726.

Hillestad, B., H Kristjánsson, Ó., Makvandi-Nejad, S., Moghadam, H. K. 2020. Genome-Wide Association Study Confirms Previous Findings of Major Loci Affecting Resistance to Piscine myocarditis virus in Atlantic Salmon (*Salmo salar* L.). *Genes*, 11, 608.

Hjeltnes, B., Bang Jensen, B., Bornø, G., Haukaas, A., Walde, C.S. (Eds.) 2019. The health situation in Norwegian Aquaculture 2018. The Norwegian Veterinary Institute. Report 6b/2019.

Jensen, P.M. 2018. Ekstremt effektivt verktøy mot lus. - Ekstremt effektivt verktøy mot lus (kyst.no) Accessed 21st May 2023.

Larsen, M.L. and I. Vormedal. 2021. The environmental effectiveness of sea lice regulation: Compliance and consequences for farmed and wild salmon. *Aquaculture*, 532, 2021,736000.

Miles, E. L., Underdal, A., Andresen, S., Wettestad, J., Skjærseth, J.B. Carlin, E.M. 2002. *Environmental regime effectiveness: Confronting theory with evidence.* Cambridge, MA: MIT Press.

Nedrejord, R. 2022. Mattilsynet ønsker automatisk lusetelling – mener den manuelle tellingen er gått ut på dato | IntraFish.no. In Norwegian.

NFD. 2021. Havbruks-strategien. Et hav av muligheter. Næring og fiskeridepartementet, Oslo.

Nilsen, R., Serra-Llinares, R.M., Sandvik, A.D., Mohn, A.M., Askeland Johnsen, I., Karlsen, Ø., Uglem, I., Bekke Lehmann, G. 2021. Lakselusinfestasjon på vill laksefisk våren 2021— Framdriftsrapport til Mattilsynet. Rapport fra havforskningen 2021–29. In Norwegian.

Olaussen, J.O. 2018. Environmental problems and regulation in the aquaculture industry. Insights from Norway. *Marine Policy*, 98, 158–163.

Olesen, I., Rosendal, G.K., Tvedt, M.W., Bryde, M., Bentsen, H.B. 2007. Access to and protection of aquaculture genetic resources: Strategies and regulations. *Aquaculture*, 272, S47–S61.

Olesen, I., Bentsen, H.B., Phillips, M., Ponzoni, R.W. 2015. Can the Global Adoption of Genetically Improved Farmed Fish Increase Beyond 10%, and How? *Journal of Marine Science and Engineering*, 3, 240–266.

Rauw, W.M., Kanis, E., Noordhuizen-Stassen, E.N., Grommers, F.J. 1998. Undesirable side effects of selection for high production efficiency in farm animals: A review. *Livestock Production Science*, 56, 15–33.

Rosendal, G.K. and Olesen, I. 2022. Breeding for lice resistance in Norwegian farmed Atlantic salmon: an ignored or insignificant path for sustainable innovation? *Aquaculture*, 548, 1–11.

Rosendal, G.K., Olesen, I., Bentsen, H.B., Tvedt, M.W., Bryde, M. 2006. Access to and legal protection of aquaculture genetic resources: Norwegian perspectives. *Journal of World Intellectual Property*, 9, 392–412.

Rosendal, G.K., Olesen, I., Tvedt, M.W. 2013**.** Evolving legal regimes, market structures and biology affecting access to and protection of aquaculture genetic resources*.* *Aquaculture*, 402–203, 97–105.

Solås, A.M., Hersoug, B., Andreassen, O., Tveterås, R., Osmundsen, T.C., Sørgård, B., Karlsen, K., Asche, F., Robertsen, R. 2015. Rettslig rammeverk for norsk havbruksnæring – Kartlegging av dagens status. Nofima rapport 29/2015. Rettslig rammeverk for norsk havbruksnæring - Kartlegging av dagens status. Nofima. In Norwegian, with English summary.

Sommerset I., Walde, C.S., Bang Jensen, B., Wiik-Nielsen, J., Bornø, G., Oliveira, V.H.S., Haukaas, A., Brun, E. 2022. The Norwegian Veterinary Institute rapportserie nr. 2a/2022, utgitt av Veterinærinstituttet 2022 Fiskehelserapporten 2021 (vetinst.no). In Norwegian, 209 pp.

Tsai, HY., Hamilton, A., Tinch, A.E., Guy, D.R., Bron, J.E., Taggart, J.B., Gharbi, K., Stear, M., Matika, O., Pong-Wong, R., Bishop, S.C. 2016. Genomic prediction of host resistance to sea lice in farmed Atlantic salmon populations. *Genetic Selection Evolution*, 48, 47.

Underdal, A. 2000. Science and politics: the anatomy of an uneasy partnership. In S. Andresen, T. Skodvin, A. Underdal & J. Wettestad, Science and politics in international environmental regimes. Manchester: Manchester University Press, UK. 240 pp.

Vormedal, I., Gulbrandsen, L.H. 2018. Business Interests in Salmon Aquaculture Certification: Competition or Collective Action? *Regulation and Governance*, 14, 328–343.

White Paper 2013. Naturens goder – om verdier av økosystemtjenester (Natural benefits – on the value of ecosystem services). NOU 2013:10, Miljøverndepartementet, Oslo. 431 pp. In Norwegian, with English summary of 38 pp.

White paper. 2014-2015. Meld. St. 16. 2014–2015. Forutsigbar og miljømessig bærekraftig vekst i norsk lakse- og ørretoppdrett. Nærings og fiskeridepartementet, Oslo. 88pp. In Norwegian.

Yin, R. K. 2003. *Case study research: Design and methods*. 3rd edition. SAGE, London, UK. 181 pp

Ødegård, J., Kjøglum, S., Medina, M., Torgersen, J.S., Korsvoll, S.A., Deerenberg, R., Yáñez, J.M., Cichero, D., Lopez, P. Moen, T. 2022. Genetics of parasite attraction in Atlantic salmon: Potential for group-level protection against sea lice. Proceedings of the 12th World Congress on Genetics Applied to Livestock Production, Rotterdam, The Netherlands, 3-8 July 2022. 4 pp.

Acknowledgements

Funding from the Research Council of Norway for project no. 294504 and project no. 294796 is acknowledged.

The responses from the anonymous interviewees are greatly acknowledged. The list of responders and transcripts of responses can be obtained upon request and possible approval of the respondents.

Appendix 1.

Guide to open questions to key actors: Breeding for lice resistance and policy instruments

1. How do you perceive the reception of the public instruments (i.e. the Traffic Light System, the Development licenses and the Brood stock licenses) aimed at stimulating sustainable innovation in reducing the sea lice problem in the salmon producing sector?

2. The Development licenses were all applied to R&D in off-shore and on-land installations. How do you perceive the scope for stimulating and applying other types of R&D to fight the sea lice problem, such as i) various forms of delousing treatments, ii) innovations in breeding for lice resistance; iii) better application of cleaner fish? Could either of these have a potential to enhance the scope for sustainable innovation to reduce the sea lice problem?

3. If relevant: How would you prefer the public instruments (licenses) to be designed and aimed (what type of innovation)?

4. Have you (your organization) considered the scope for selective breeding as an option for dealing with the sea lice problem in aquaculture? (i.e. in terms of reducing the sea lice problem and/or enhancing fish health.)

5. To follow up on the last question: How do you perceive the state of knowledge concerning selective breeding as an innovation strategy?

6. How would you describe your contact with the salmon producing sector and the breeding corporations (formal meetings, frequency)? (This question was posed to NGOs and to the public authorities that are responsible for managing the aquaculture sector.)

6a. How would you describe your contact with the authorities that are managing the salmon producing sector and the breeding corporations (formal meetings, frequency)? (This question was posed to the salmon farmers and breeders).

7. Delousing treatments have been cited as an increasing threat to fish health in the salmon producing sector. How can the persistent use of these treatments be accounted for?

8. How do you perceive the scope for the authorities in affecting the breeding goals in the salmon breeding programmes?

9. Salmon farming in Norway is regulated by three different ministries and their directorate. In your opinion, how does this organization affect the scope for your (ministry, directorate) to impact management and sustainability in the sector? (This question was posed to various parts of the management and regulatory system for the salmon breeding sector.)

Appendix 2

Table A. Number of cages, sites, and license capacities (maximum allowed biomass in tons) in operation in 2021 in Norwegian counties based on ordinary salmon licences and based on specific salmon licenses (Brood fish, Development, Green and Researcher licences).

Type of licences/Counties	No cages	No sites	Capacities, tons
Troms & Finnmark	820	162	339 541
Nordland	860	190	333 990
Trøndelag	551	130	246 299
Møre & Romsdal	413	78	166 324
Vestland	857	247	242 172
Rogaland & Agder	252	63	94 744
Broodfish and all other specific Licences	263	56	20 369
All 13 production areas	17 to 519	5 to 124	8 244 to 252 416

Source: Directorate of Fisheries, Number of licenses, sites and license capacities (maximum allowed biomass). Data reported 20.12.2021.

Table B. Number of license capacities (maximum allowed biomass in tons) and sites in operation in 2021 in Norwegian salmon-production areas based on ordinary licences and based on specific licences.

Type of licenses/ Production areas	Capacities, tons	No sites
Area 1: From Swedish border to Jæren	22 118	10
Area 2: Ryfylke	64 286	39
Area 3: From Karmøy to Sotra	154 323	124
Area 4: From Nordhordland to Stadt	86 507	118
Area 5: Stadt til Hustadvika	69 439	37
Area 6: Nordmøre og Sør-Trøndelag	252 416	109
Area 7: Nord-Trøndelag med Bindal	111 089	54
Area 8: From Helgeland to Bodø	161 757	78
Area 9: Vestfjorden and Vesterålen	147 158	85
Area 10: From Andøya to Senja	119 616	57
Area 11: From Kvaløy to Loppa	78 351	35
Area 12: Vest-Finnmark	127 399	63
Area 13: Øst-Finnmark	8 244	5
Broodfish and all other specific Licences	20 369	56
Total	**1 423 070**	**870**

Source: Directorate of Fisheries, Number of licenses, sites and license capacities (maximum allowed biomass). Data reported 20.12.2021.

Tables

Table 1: Summary of assumptions: how the state of scientific knowledge may affect the choice of developing policy instruments to stimulate LR breeding

A0: Scientific discord on LR, hence	no policy incentives for LR breeding
A1: Scientific agreement on LR, but	…high conflict of interests reduces impact of science on policy = no policy incentives for LR breeding
A2: Scientific agreement on LR, but	…high saliency reduces impact of science on policy = no policy incentives for LR breeding
A3: Scientific agreement on LR, but	…administrative complexity reduces impact of science = no policy incentives for LR breeding

Annex 2

Table A. Number of cages, sites, and license capacities (maximum allowed biomass in tons) in operation in 2021 in Norwegian counties based on ordinary salmon licences and based on specific salmon licenses (Brood fish, Development, Green and Researcher licences).

Type of licences/Counties	**No cages**	**No sites**	**Capacities, tons**
Troms & Finnmark	820	162	339 541
Nordland	860	190	333 990
Trøndelag	551	130	246 299
Møre & Romsdal	413	78	166 324
Vestland	857	247	242 172
Rogaland & Agder	252	63	94 744
Broodfish and all other specific Licences	263	56	20 369
All 13 production areas	17 to 519	5 to 124	8 244 to 252 416

Source: Directorate of Fisheries, Number of licenses, sites and license capacities (maximum allowed biomass). Data reported 20.12.2021.

Table B. Number of license capacities (maximum allowed biomass in tons) and sites in operation in 2021 in Norwegian salmon-production areas based on ordinary licences and based on specific licences.

Type of licenses/ Production areas	Capacities, tons	No sites
Area 1: From Swedish border to Jæren	22 118	10
Area 2: Ryfylke	64 286	39
Area 3: From Karmøy to Sotra	154 323	124
Area 4: From Nordhordland to Stadt	86 507	118
Area 5: Stadt til Hustadvika	69 439	37
Area 6: Nordmøre og Sør-Trøndelag	252 416	109
Area 7: Nord-Trøndelag med Bindal	111 089	54
Area 8: From Helgeland to Bodø	161 757	78
Area 9: Vestfjorden and Vesterålen	147 158	85
Area 10: From Andøya to Senja	119 616	57
Area 11: From Kvaløy to Loppa	78 351	35
Area 12: Vest-Finnmark	127 399	63
Area 13: Øst-Finnmark	8 244	5
Broodfish and all other specific Licences	20 369	56
Total	**1 423 070**	**870**

Source: Directorate of Fisheries, Number of licenses, sites and license capacities (maximum allowed biomass). Data reported 20.12.2021.