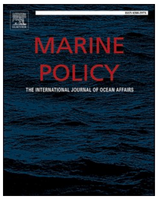
Marine Policy 117 (2020) 103942

Contents lists available at ScienceDirect

Marine Policy

journal homepage: http://www.elsevier.com/locate/marpol



Environmental policy and innovation in Norwegian fish farming: Resolving the sea lice problem?

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ARTICLE INFO

Keywords:
Sustainable aquaculture
Innovation policy
Research and development
Sea lice

ABSTRACT

In Norway, the world's largest salmon-producing country, reducing sea-lice levels in fish farms has been an overarching goal of government policy since 2013. However, industry innovation has not yet succeeded in significantly reducing the sea lice problem.

We identify two main types of radical environmental innovation that could potentially resolve the sea-lice problem: in-shore closed-cage production technology, and a genetically lice-resistant salmon. Furthermore, we provide an analytical framework that shows how radical environmental innovations with a "public good" character are least likely to receive private R&D funds. This leads us to conclude that neither in-shore closed cage technology nor targeted breeding towards lice-resistance will succeed in the market unless backed by targeted government intervention.

Closer examination shows that these two types of innovation have been less prioritized, if at all, in recent policy interventions. First, the government has geared most of financial support towards relieving the risk of investment in offshore innovation projects, although inshore projects might be better suited for accommodating public and environmental needs. Second, this study underscores the need and potential for stimulating sustainable innovation through the genetic route—a point overlooked in Norway's current policy mix.

1. Introduction

Fish farming is the world's fastest-growing food-producing sector, now accounting for half of seafood consumption worldwide [1]. From being a small, experimental business in the 1970s, salmon farming has become a highly profitable and global industry, today representing about 90% of the salmon market [2]. However, this rapid growth and industrialization has had substantial environmental repercussions [3]. Among the most severe and persistent problems has been the proliferation of sea lice, a parasite that thrives in fish-farming localities and infects surrounding habitats, with potentially detrimental consequences for wild salmon and trout populations [4,5]. In Norway, the world's largest salmon-producing country, reducing sea-lice levels in fish farms has been an overarching goal of government policy since 2013. This article offers a conceptual analysis of incentives and conditions for stimulating various types of environmental innovations for solving the sea-lice problem. Innovation types are classified along a taxonomy, showing why radical[1] environmental innovations with a "public good" character are least likely to be adopted without targeted government intervention. Next, this study reviews Norway's new, lice-focused policies, assessing their effect in terms of stimulating certain types of innovations, and evaluating whether they address existing intervention needs. In conclusion, the prioritization of support to new, offshore production technologies is found to represent a side-track that diverts attention from the need to promote radical innovations that can resolve the sea-lice problem in existing farming areas. To stimulate radical environmental innovations with a "public good" character, the government must emphasize support to in-shore production technologies such as closed cage-pens, and the promising, but unrealized, potential for genetic breeding of lice-resistant salmon.

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[1] When an innovation is *radical,* it is typically designed to replace existing technologies, and has a potential to fundamentally transform an industry. In other words, it involves the development and application of an entirely new practice, production method, process or product. This contrast with *incremental* innovations, which typically involves minor improvements or upgrades to established technologies and does not have the power to change or shake an industry [22]; Kemp et al., 1998).

https://doi.org/10.1016/j.marpol.2020.103942
Received 20 December 2019; Received in revised form 2 March 2020; Accepted 12 March 2020

2. Fish farming in Norway

Modern production methods for fish farming developed in Norway in the late 1960s, when local farmers begun to experiment with breeding salmon and trout in open-net pens or cages, typically located in sheltered bays and fjords along the coast. Breeding programs for genetic improvements commenced in the early 1970s, achieving a 30% increase in salmon growth rates after only two generations, as well as favorable genetic correlations between growth rates, feed conversion rates, and disease resistance [6–8]. Since the 1990s, Norwegian salmon farming has undergone massive growth and industrialization. From being small-scale and often locally anchored businesses, fish-farms have increasingly merged, restructuring into big, multinational companies [9, 10].

This dramatic transformation is reflected in Figs. 1 and 2. Fig. 1 shows the development in production volumes of salmon and sea trout 1994–2017 on the left Y-axis, and the development in unit costs and prices on the right Y-axis.[2] Volumes grew from around 200,000 tons to more than 1300 thousand tons in 2017: a doubling after 2005. However, production output has stagnated after 2012.

The development in cost per kilo displays a similar trajectory.[3] Unit costs dropped dramatically during the 1990s in tandem with the growth in production. However, unit costs after 2001 show a moderate increase. The stagnation in production volume and productivity improvements may be explained by deepening environmental problems. For instance, the costs of sea-lice management have become substantial. From 2008 to 2015, "other production costs," of which sea-lice treatment constitutes 80%, rose from an average of 0.36–0.68 US$ per kg.

Despite the increase in unit costs, the industry has never been more profitable. The reason is that the increase in unit costs has been more than compensated by increases in the prices of salmon and trout. As we can see from Fig. 1, the price per kilo salmon has increased from about $7 to $12 from 2012 to 2017 dwarfing the increase in "other production costs" caused by deepening environmental problems.

In Fig. 2, extra-normal profits are shown on left Y-axis, and extra-normal return to capital on the right Y-axis. Extra-normal profits are defined as profits after a 4% real rate of return to capital is deducted; excess return to capital is defined as the return to capital above the 4% rate.[4] Note that the extra-normal profit of the sector was more than 2.5 billion US$ in the period 2016–2018. Moreover, excess return has remained above 60% from 2013 onwards.

Such extraordinarily high profitability naturally creates high industry demand for more growth. Production volumes are regulated through a government permit system,[5] which entitles private companies to produce a specific amount of fish (measured as maximum allowed biomass per company permit) at assigned fish-farming localities.[6] Industry pressure on the authorities to issue more permits has grown, but the government has been reluctant to issue new permits—as reflected in the recent stagnation of production volumes—due primarily to the unresolved environmental problems, sea-lice proliferation in particular.

3. Sea lice and fish farming

3.1. The challenge

Sea lice is a parasite that feeds off the salmon's flesh and skin. In the wild, sea lice are not naturally abundant, thanks to the salmon's periodic change of habitat from salt to fresh water, which prevents the sea lice from thriving. But the growth in fish farming and greater stocking density within production localities has brought a 100-fold increase in sea-lice hosts. Many scientists and wild-fish interest organizations see this as the most significant threat to surrounding wild salmonid populations [4,5,11]. Particularly vulnerable are the young, wild salmon smolt that pass by farming areas en route to their offshore winter habitat. Infections of more than 10 lice are likely to cause fish mortality [12]. Between 2010 and 2014, annual losses of wild salmon from sea lice was estimated at approximately 50,000 [13].

The sea-lice threat has also accelerated the need for de-lousing measures, which can seriously worsen caged-fish welfare and increase mortality rates [14]. Measures for removing lice include the use of chemicals such as hydrogen peroxide, known to threaten wild coastal shrimp and other shellfish stocks [15], and medicines such as diflubenzuron and teflubenzuron.[7] Due to the parasite's growing resistance to medicines, methods for mechanical delousing have increased substantially, including the use of "hydrolicers" (lice removal using water pressure in a closed column), or fresh and warm water flushing. However, this escalation in mechanical delousing measures also correlates with a significant rise in fish mortality since 2013 [16]. In 2018, the median mortality rate of caged salmon was 15%, some of which might be caused by poor smolt quality and infectious fish-diseases, but also due to increased injury or stresses from the rise in delousing measures [17]. Further, the use of lice-eating species, including various types of wrasse and lumpfish that feed on sea lice and function as "cleaning fish," has also raised welfare issues, as the mortality rate of these species within production cages is high [18].

Another lice-related challenge is fish escape as the result of storms, predators or human error: approximately 200,000 salmon escape yearly from Norwegian fish-farms, which equals about half of the wild salmon returns to Norwegian rivers [13]. Caged-fish escape may exacerbate the sea-lice situation by transporting lice into the commons, where they can infect passing wild salmonids. It also leads to hybridization of the gene pool, as the natural population becomes gradually dominated by escapee offspring, lacking characteristics crucial to survival and adaptation to conditions in the wild [14].

The Norwegian government aspires to quintuple fish production by 2050 to become the world's leading seafood nation, but recognizes that this will require a significant reduction of risks to the health and survival of wild stocks. A major instrument for resolving the sea-lice problem is industry innovation in new lice-reducing methods, measures and technologies.

3.2. Four types of sea-lice reducing innovations

Innovation has been instrumental both for increasing productivity in fish farming and for reducing the environmental impact of fish farming [19]. The industry has applied many forms of environmental innovation aimed at reducing the occurrence of sea lice in fish farms, however, the industry has not yet succeeded in this area of innovation. These innovations can be categorized on a spectrum from incremental to radical [20]. *Incremental innovation* involves minor improvements or upgrades to existing "technological regimes" of established engineering practices, production processes, technologies, product characteristics, methods,

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[2] Based on data from the Norwegian Fishery Directorate.

[3] Cost are measured in US$ per kilo, adjusted to yields in constant 2018 prices by the Norwegian price index.

[4] Based on data from Statistics Norway's national accounts: figures on gross product, capital investment, capital consumption and labor use.

[5] Permits are distributed to companies by the Ministry of Trade, Industry, and Fisheries through allocation rounds. Companies compete to satisfy the government criteria for new permits, which the Fisheries Directorate then distributes to winning firms, either for a fixed price or through an open or closed auction requiring pre-qualification. The total number of permits by 2018 was 1,075, spread over approximately 1000 localities along the Norwegian coast [30]. See Ref. [28] for an in-depth analysis of Norway's permit system.

[6] The MAB limit is generally 780 tons, except in northern Norway (Troms and Finnmark counties), where it is 945 tons.

[7] On the positive side, the use of antibiotics is very low: 0.20 mg pr kg fish in 2015, down from 887 mg in 1987. By comparison, in Chile the use was still 660 mg pr kg in 2015. See Ref. [12].

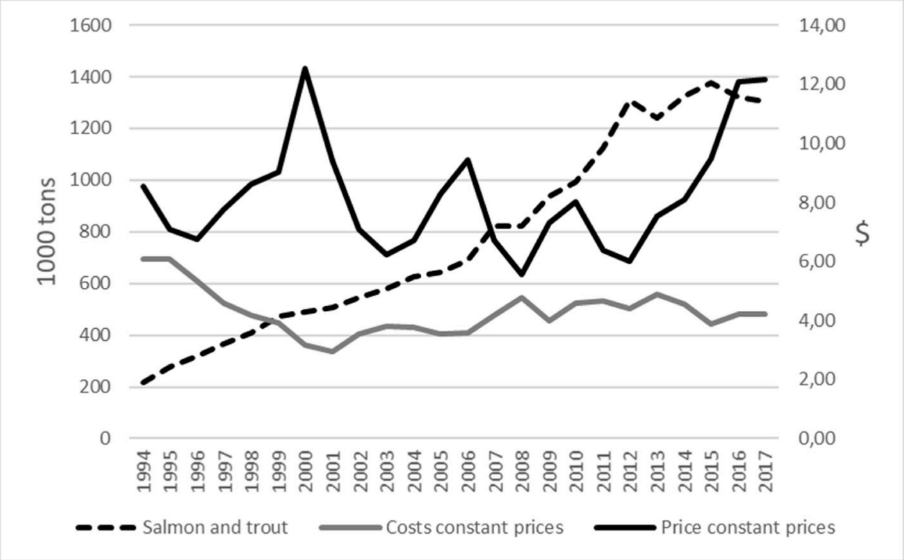

Fig. 1. Development in production volumes and unit costs, US$/kilo.

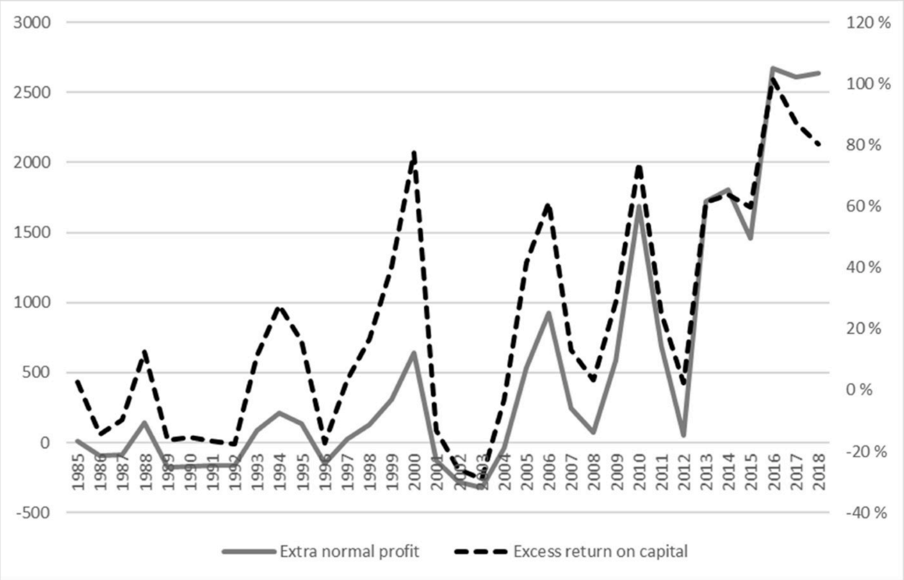

Fig. 2. Profitability of Norwegian fish farming, mill US$.

skills and procedures of a given sector—the *modus operandi* of an industry [21]. *Radical innovation*, by contrast, involves the development and application of 0entirely new practices, production methods, processes or products, designed to replace existing technologies, with the potential of fundamentally transforming an industry's *modus operandi* [22]. Radical innovation requires a large up-front investments, and often involves high economic risk. This study categorizes existing, lice-related innovation activities in four broad groups:

1) *medicinal* innovation, which refers to lice-reducing medicinal and chemical treatments such as hydroperoxide and teflubenzuron, widely used by Norwegian fish producers. However, the sea louse has proved extremely adaptable and increasingly resistant, reducing the effectiveness of medicinal and chemical tools [12]. The government has therefore sought to limit the use of such treatment. We thus consider new medicines and chemicals to represent incremental innovations that are ultimately unable to resolve the sea lice problem.
2) *biological* innovation, involving experimentation with and increasing use of lice-eating fish such as wrasse and lumpfish—which feed on the sea lice, cleaning the salmon within production cages—has also been widely adopted by the industry. However, the overharvesting of lice-eating species and ethical welfare issues linked to high mortality rates (33% for wrasse and 48% lumpfish after only 6 months),[8] raise doubts about the viability of biological de-lousing methods, which we consider to represent a form of incremental innovation with limited potential for resolving the sea-lice challenge.
3) *genetic* innovation, involving selective breeding methods and technology to boost fish resistance to lice throughout the production cycle, has received increasing attention over the past 5–10 years.

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[8] Since the expansion in lice-eater application up until 2011, the WWF has been critical to continued growth in the use of lice-eaters https://www.wwf.no/bibliotek/nyheter_fakta/nyhetssaker/?33089/Krever-god-forvaltning-av-leppefisk accessed 02.10.2018. See also [12].

Breeding companies are now slowly starting to invest in developing more lice-resistant salmon roe on a small scale, and recent results appear promising.[9] In 2018, the international breeding company AquaGen reported a 60% reduction of lice-infestation using new methods for "genomic selection."[10] Genetic innovation thus appears to have sizeable potential for reducing sea-lice levels in fish farms, but prioritizing this innovation type also involves high risks and high costs. How long it may take to breed effectively resistant salmon remains uncertain, while the addition of lice-resistance as a further breeding goal is likely to bring a temporary decline in other profit-enhancing traits and functions—such as high growth rates through enhanced ability to absorb feed nutrients and various types of disease resistance. During this temporary decline, fish producers choosing a more lice-resistant roe would probably have to incorporate the added cost of slower fish growth until the functionality of existing traits was recovered. Therefore, genetic innovation for solving the sea-lice problem as seen as a *radical* innovation.

4) *mechanical* innovation, referring to the development of new production equipment, methods and installations, has increased substantially over the past decade —by far the most among the four innovation types identified here [16]. This includes incremental innovations to existing open-net cage production technology, such as lice-skirts or sensor and digitalization technologies, but also radical innovations clearly differing from the other key element of the industry's *modus operandi:* the use of open-net cages. Installations and methods for closed-cage production, subsea production, and offshore production—the latter designed for less sheltered, open sea areas unfeasible for traditional open-net cages due to complex wind, current and wave conditions—are currently being tested through a special type of government development permit [16].

4. A model of environmental innovation in fish farming

Bergesen and Tveterås [23] provides a rich description of the innovation system in Norwegian fish farming. In this article, we apply a bird's eye view on the innovation process abstracting from the different actors and the knowledge flows between them. As shown Fig. 3, we divide the innovation process into three stages, starting with research and development (R&D). Next, successful ideas are sold to early adopters, and these ideas are further refined through a learning process in which the unit cost of the new technology falls and the design improves as producers gain experience. The final stage is widespread market diffusion, with the new technology becoming the new standard.

Private companies will not invest in R&D or in early market trials if they do not believe that their ideas will eventually have success in the market. In the innovation literature, this incentive to conduct R&D is often termed *market pull.* Intellectual property rights (IPR) are central for creating a market-pull force, incentivizing innovators to invest in the early stages of an innovation process, in expectations of recovering their investment by gaining a temporary monopoly on the idea. Even with IPR, it is generally accepted that R&D will prove insufficient if governments do not supplement the market-pull force with *technology-push* strategies. Technology push may be applied to both the first and the second stages of the innovation process—to promote both R&D and early adoption of the new technology. Examples of technology push strategies are subsidies to private R&D, public R&D programs, subsidies to investments in new technology and government procurement of new technologies.

Radical innovations are generally held to require more technology push than incremental innovations. One argument is that more risk is involved, and that firms may be more risk averse than desirable from the point of view society as whole. In this case social welfare would improve with more investment in radical technologies. Otherwise, governments are chary of prioritizing between projects when applying technology push, that is, governments are reluctant to subsidize some types of radical innovations more than others. Instead, they prefer to support all types of radical innovation by some fraction of their costs, and then let the market decide the winner(s). In fish farming, however, such technological neutrality might not be desirable regarding innovation.

4.1. *Private versus public benefits of innovation*

Innovations in fish farming will differ as to whether they are strictly profitability-enhancing or also sustainability-enhancing. Strictly *profitability-enhancing innovations* increase the profit from a production permit, independently of the actions of other permit-holders. For instance, a permit-holder owner who starts to use a new and more effective feed will increase her profits independently of what feed the other permit-holders use. Moreover, even if all farms change feed and the market price of farmed fish decrease, the individual farmer has no incentive to go back to the old, less effective feed. Since the price has fallen, changing back would mean even lower profits than before.[11] Thus, a profitability-enhancing innovation has the character of a *private good* for which the demand for the good is independent of what the other actors in the market do. Typically, IPR work well in promoting this type of innovation.

Environmental innovations, on the other hand, are innovations that reduce the negative environmental impacts of a fish-farming permit, or from fish-production more broadly. As environmental problems affect all producers in an area, the adoption of an environmental innovation by one permit owner is likely to affect other permit owners positively. For example, one producer's adoption of a technology that reduces sea-lice levels within a farming pen or locality is also likely to benefit neighbors by lowering the sea-lice infection pressure within the production area more generally. This may provide fish-farming companies with incentives for freeriding on other companies' adoption of such innovations. An environmental innovation therefore has the character of *both a private and a public good.* IPR may not work as well in promoting this type of innovation, as adoption by one fish farm could reduce the incentives for other farmers to adopt.

4.2. *Adoption of environmental innovations*

In Fig. 4 we study adoption of environmental innovations as a game between two players. For all firms that adopt an environmental innovation, it will be assumed that there is an investment cost that accrues solely to the firm that adopts. The size of this investment cost will typically depend on whether the innovation is radical or incremental. Furthermore, in the game below, it is assumed that current regulations do not require any of the firms to adopt.

If no license owner adopts the innovation, the pay-offs are zero: the status quo. The letters a,b and c then refers to the private *net pay-offs* of the fish-farming license operators if at least one of the players adopts. The net pay-offs consists of the increase in profits due to lower environmental costs subtracted the investment costs (if the farm has adopted).

If two firms adopt, they both get $a > 0$; this situation is preferable to the status quo. If only one firm adopts the innovation, this firm gets $b < a$ since the sole adopter does not get the public benefit from the other firm adopting. How much smaller b is compared to a will depend on the public benefits involved. The firm that does not adopt gets $c > 0$: it

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[9] In a project supported by the RCN and FHF, Gjerde (2012) found a 75% reduction in lice per fish after five generations.

[10] See for example [34], Effective lice control through breeding and genetics, URL: https://aquagen.no/en/2016/08/15/effective-lice-control-through-breeding-and-genetics/and Kyst.no. 2018, Effektivt verktøy mot lus, https://www.kyst.no/article/ekstremt-effektivt-verktoey-mot-lus/.

[11] We thank one of the referees for pointing this out.

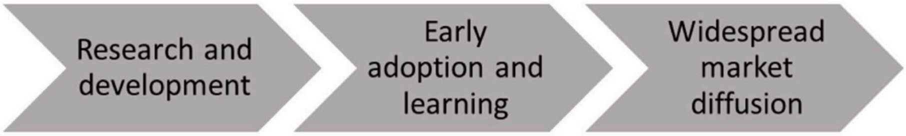

Fig. 3. The innovation process.

	Adopt	Not adopt
Adopt	a,a	b,c
Not adopt	c,b	0,0

Fig. 4. Adoption of environmental innovations.

benefits from the fact that the other firm adopted, but does not have to pay the investment cost. For the following discussion, it is assumed that $2a > c + b$: it is socially preferable for both firms to adopt.[12] The relative sizes of a, b and c will determine the outcome of the adoption game. The following two alternative emerge:

4.2.1. *Full adoption*

If $a > c$ and $b > 0$, the solution of the game is trivial, as both license owners adopt the innovation. Here it is optimal to adopt, independently of what the other player chooses. However, the private benefit of adoption must be relatively important, and the investment costs cannot be too high compared to the private benefit. This is most probably a case of incremental innovation. Clearly, government involvement in the adoption decision is not needed here.

4.2.2. *Insufficient adoption*

If, on the other hand, $a > c$ but $b < 0$, there is a collective action problem: it no longer pays off to be the sole adopter. This may occur if the public benefits of the innovation overshadow the private benefits. On the other hand, there are no incentives for freeriding on the adoption of the other firm if $a > c$. This may indicate that the investment cost is not prohibitively high. There are two Nash equilibria in this game: either no adoption of the innovation, or full adoption. If the license owners happen to coordinate on the "no adoption" equilibrium, government involvement in the adoption decision will be desirable.

If $a < c$ and $b > 0$, this becomes a game of "chicken". Both firms would like to free-ride on the other firm and not adopt—which indicates that the private investment cost is potentially high, e.g. the technology may involve a radical shift away from the *modus operandi*. On the other hand, a firm that adopts will not regret its adoption decision, as $b > 0$. There are two Nash-equilibrium in this game both involving one of the firms adopting and the other not. Clearly, in a real situation, both firms may wait for the other firm to adopt, and hence, they will be stuck in the status quo. Since it is socially optimal that both adopt, government involvement in the adoption decision is desirable.

Finally, $a < c$ and $b < 0$, we have both a free-riding and a collective action problem. Either of the firms would like to free ride on the other firm and not adopt. Moreover, not adopting is preferable to being the sole firm that adopts. The reason may be that investments costs are high, and that the public benefits of the innovation are relatively more important than the private benefits. Hence, in order to defend the high investment costs, both firms must adopt. In this game, there is only one Nash equilibrium in this game: no adoption of the innovation. In this case, government involvement in the adoption decision will be detrimental.

The essential message here is that there may be innovations that are socially desirable, but that will not diffuse into the market, or only partly. This of course has consequences for private incentives to innovate. A firm is unlikely to invest in the development of an environmental innovation that involves either strong free-riding incentives $a < c$ and/or a collective action problem $b < 0$. IPR will not work as intended for such innovations, and technology push strategies may have to be applied to both the R&D stage and in the early adoption phase.

4.3. *A taxonomy of innovations in fish farming*

In Fig. 5 we categorize the types of innovations identified in Section 3.2. On the vertical axis we divide innovations into those which have mainly private benefits and those which also have significant public benefits. On the horizontal axis we sort innovations by the extent to which they are incremental or radical. As noted, radical innovations tend to demand higher upfront investments, involve higher risk and less certain benefits. Lastly, we illustrate the need for government involvement in the innovation process by the degree of shading of the four quadrants – the more shaded, the more essential are technology push measures such as subsidies to R&D and subsidies to investment in the new technologies.

In the bottom left quadrant of Fig. 5 are incremental innovations with a "private good" character. Examples are more effective feed and developing higher value marketing channels. Then in the upper left quadrant we have incremental environmental innovations such as the use of cleaning fish, chemicals or lice skirts for open-net pens. The application of these methods reduces sea lice in a pen, and hence also contributes to reducing lice levels in neighboring localities. On the other hand, application of these methods is required if lice levels in a pen exceeds a certain threshold, and thus, there is a market pull for these types of environmental innovations. Consequently, technology push strategies become relatively less important.

In the two right quadrants of Fig. 5 we have radical innovations such as closed-cage and offshore production technology, and genetic breeding. Closed pens designed to replace the open pens in sheltered areas may have considerable private benefits, as the producer is effectively shielded from fish disease and sea-lice infections that can easily spread through open waters. However, the public benefits are also high, as the adoption of closed-cage production at one farming locality will reduce the overall lice pressure markedly within that area, lessening problems for surrounding, open-net farms. Thus, the innovation process for closed production cages designed to replace the open pens is placed in the upper right quadrant of Fig. 5.

Offshore production is in the bottom right quadrant of Fig. 5, as the technology is likely to have substantial private benefits: producers are more likely to be shielded from fish disease and sea-lice infestations than farms in existing, inshore localities. Offshore production can further unlock the potential for company growth in production volumes precisely by being located in new areas less likely to contribute to lice-induced mortality among wild stocks. However, the public-good component of offshore production is questionable as long as it is not

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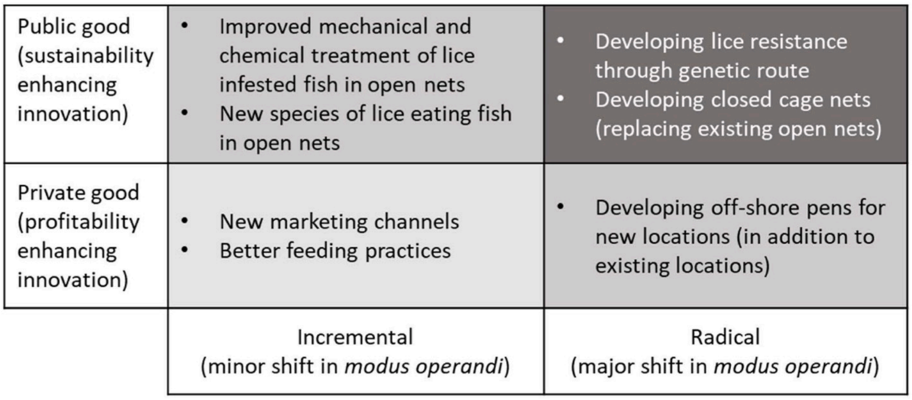
[12] In addition there may be an environmental benefit δ per firm that adopts which is not likely to be taken into account by the firms. The environmental benefit may make it desirable that both firms adopt even if $2a < c + b$. We thank one of the referees for pointing this out.



Public good (sustainability enhancing innovation)	• Improved mechanical and chemical treatment of lice infested fish in open nets • New species of lice eating fish in open nets	• Developing lice resistance through genetic route • Developing closed cage nets (replacing existing open nets)
Private good (profitability enhancing innovation)	• New marketing channels • Better feeding practices	• Developing off-shore pens for new locations (in addition to existing locations)
	Incremental (minor shift in *modus operandi*)	Radical (major shift in *modus operandi*)

Fig. 5. A taxonomy of fish-farming innovations.

intended to replace open-net pens in current localities. In other words, it does not contribute to reducing the occurrence of sea lice in existing farming areas, or to the need to reduce infection pressure on wild stocks. Thus, public support to this technology may be less desirable than for other types of environmental innovations.

Finally, genetic innovation is also in the upper right quadrant of Fig. 5. Traditional, selective breeding is by nature incremental, as breeding programs must continuously introduce new and diverse genetic material in order to maintain the core breeding goals of high growth and feed efficiency. Also, the addition of new breeding goals is by nature incremental, as seen in the case of resistance to IPN (infectious pancreas necrosis), which has already rid the salmon farming sector of very costly outbreaks.[13] However, the more quickly new breeding goals are added, the higher the risks related to temporary loss in growth rates. Therefore, the urgency involved in developing a "fully" lice-resistant fish makes genetic breeding a *radical* type of innovation: Its use by fish producers may involve at least a temporary break with the industry's *modus operandi*, namely the use of a fast-growing and thus highly profitable salmon roe, entailing high up-front investments and risks for early adopters. The public-good character of genetic innovation is also high, as one producer's use of lice-resistant fish will be highly beneficial, reducing for surrounding farms as well [24,25,33].[14] With a partly but not completely resistant fish type, genetic innovation might be effective only if almost all farms adopted. These features make the reluctance to rely one-sidedly on lice-resistant fish in breeding programs resemble a game of chicken.

Finally, patenting is rarely suited or applied to protect breeding results [26,27].[15] Unlike IPN resistance, where patenting was possible through the application of a specific genetic marker (QTL), lice-resistance involves far more genes and is thus less amenable to patenting.[16] This clearly makes technology push strategies even more crucial.

This taxonomy and discussion of incentives and conditions for adoption of various types of lice-reducing environmental innovations shows that *targeted government intervention is needed to stimulate radical, environmental innovations with a public-good character*. Examples of such innovations include closed-cage production and genetic breeding for a lice-resistant salmon. As these may depend on policy support for successful market diffusion, they unlikely to receive sufficient private investment.

The next section focuses on new environmental, highly sea-lice-focused policy regime implemented by the Norwegian government after 2013, its effects on industry innovation, and the extent to which it meets the intervention needs identified in the discussion above.

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[13] Since 2010, SalmoBreed has offered roe with IPN resistance, in turn largely eliminating this virus disease. See URL: http://salmobreed.no/history/[accessed 8 May 2019]. Other typical diseases have been sought treated with vaccination, such as pancreas disease (PD) and infectious salmon anaemia (ISA), but vaccination is costly and the diseases still occur.

[14] Gjerde, 2012 http://forskning.no/fisk-fiskehelse-oppdrett/2013/08/vil-avle-fram-laks-som-ikke-frister-lus.

[15] As shown by Ref. [26]; continuous upgrading is the most common method to protect breeding results; it is a much weaker protection than patenting but does not hamper access to breeding material for other breeders. Most of the patents in aquaculture are found on feed, on vaccines and on technical equipment relating to fish farming. There is a remaining scare among companies that fish breeders may face a situation where they must choose between different traits to include in breeding programs, as the traits have been patented by different companies.

[16] Biologically, the aquaculture sector has been less suited to the use of IPR compared to plants; mainly for reasons of genetic homogeneity often required by IPR (including patents and the UPOV plant breeders' rights). Fish populations are not patentable and animals such as fish generally need an even higher degree of genetic heterogeneity to stay healthy and avoid inbreeding, compared to plants. Nevertheless, through the application of gene technology (including CRISPR and identification of marker genes), IPR may also be applied to genetic resources in aquaculture. Moreover, the tendency of applying for process patents to breeding techniques observed in farm animal breeding might become relevant for fish farming. Hence, there may be a drive towards more short-term quick fixes involving molecular genetics and this might be at the expense of more long-term selective breeding technology. However, application of molecular technologies such as genomic selection also presupposes properly managed selective breeding programmes see e.g. Ref. [31].

5. The new policy regime and industry innovation

Around 2012, public concerns regarding the negative environmental impact of fish farming were mounting. The government had received strong criticism from the National Audit Office for its lack of control over the sea-lice situation, and for having prioritized growth over the protection of wild salmonid stocks [16,28]. In response to the heightened demand for stricter industry regulation, the government has since introduced several new policies and regulations aimed at reducing sea lice, and at stimulating innovation that could help resolve this challenge.

First, the government scaled up the use of command-and-control regulations. In 2013, they imposed a general sea-lice limit of maximum 0.05 adult female lice per fish for all permits. This was further tightened in 2017, requiring levels below 0.2 in the most "vulnerable" weeks (weeks 16–22), which is the migration period for wild smolt. All permit-holders were also obliged to count and report the number of lice per fish every week throughout the year at all production localities, and to slaughter in accordance with breaches of the new lice limits. Also in 2017, the government introduced a new category of "green permits," which required sea-lice levels of between 0.25 and zero, and the demonstration of a new production method or equipment that would reduce sea lice and/or escapement.[17] In 2015, applications for "capacity increases" (permission to increase the MAB limit for existing permits) were made conditional on keeping lice-levels below 0.2 at the relevant farming localities. And in 2017 the government launched a whole new production-growth regime, the Traffic Light System (TLS). The TLS combines negative sanctions and positive rewards to regulate growth and reduce sea lice simultaneously. It divides Norway into 13 production areas (PAs), in which the infection pressure on wild salmon is measured on a biannual basis. Companies within a PA deemed to have an "acceptable" impact on wild salmon ("green light") may apply for capacity increases of up to 6% and may participate in auctions for new permits. Companies within a PA deemed to have a "moderate" impact ("yellow light") are allowed only to maintain current production volumes, whereas companies within a PA deemed to have an "unacceptable" impact will be collectively punished with requirement to reduce production volumes by 6%. However, the regime includes an additional provision: companies in "yellow" and "red" areas that can demonstrate sea-lice levels below 0.1 may also apply for capacity increases.

Stricter standards and regulations aimed at limiting an environmentally harmful activity or output are generally expected to stimulate incremental innovation by creating a market "pull" for new and improved methods, techniques or equipment that facilitate compliance. A complete analysis of all industry innovation motivated by stricter regulation after 2013 is beyond the scope of this study. However, as shown by Vormedal et al. [16]; new delousing measures and actions implemented by fish farmers—which include incremental biological and chemical innovations, such as hydrogen peroxide baths or the use of cleaning fish—have increased dramatically after 2013. After 2015, the use of new mechanical methods for removing lice, such as "hydrolicers," has also increased considerably.

Second, the government has sought to stimulate innovation more directly through new permits that indirectly subsidize the demonstration of innovations by giving firms a significant discount on the permit price. Such forms of government support are typically expected to create a technology "push" that can increase the supply innovations [32]. In 2013, 10 of the green permits issued (category C) provided this type of policy push: winning firms were charged only a symbolic fee of $1250, in contrast to category A and B of green permits, which were subject to auctioning. The innovation requirement for C permits was to demonstrate a radically new production technology or method that could reduce sea lice or escapement. In 2015, the government launched yet another category of "development permits." This arrangement concerned large-scale, technology projects involving considerable capital investment, financial risk, and the demonstration of a radical innovation with high potential for resolving the sea lice, escapement and/or area challenges. Development permits are allocated free of charge to successful applicants for up to 15 years, and may be converted into a commercial permit for only $1.25 million upon completion of the demonstration project. However, permit-holders are not required to *use* the innovation upon conversion. Given the current market value of $19 million for commercial permits,[18] development permits contain a generous discount of more than 90% and the opportunity to recover earlier investments after early adoption. Politically, as expressed in the legal requirements attached to the arrangement, the overarching goal of this policy instrument was for the new technologies to benefit the industry as a whole.

Figs. 6 and 7 provide a quantification and classification of all innovations implemented through green permits and development permits. Here, we present the percentage of permits categorized as medicinal, biological, mechanical and genetic respectively, out of the total amount of permits.[19] Regarding green permits, 67% of the permits represent innovations of the mechanical type, while 19% of the permits apply biological and 14% genetic innovations. As regards development permits, all permits represent innovation projects of the mechanical innovation.

Fig. 8 shows the distribution of all new, government permits issued between 2012 and 2018 by innovation type. We see that most innovations realized as a result of these new permits have been of the mechanical type (70%). These include radical innovations, such as closed-cage and offshore installations.[20]

However, as shown in Fig. 9, offshore production technologies have received the large majority of biomass growth made available through development permits. Whereas offshore project received nearly 40,000 tons in production growth, closed-cage projects received less than 1000, and thus only a fourth of what was allocated to offshore projects.

As discussed, offshore fish production technologies can resolve area challenges, thereby unlocking the potential for further growth, which

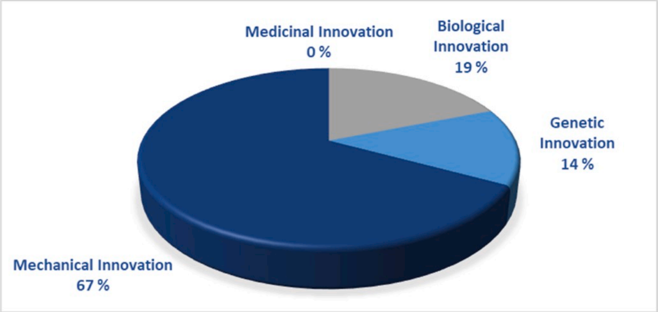

Fig. 6. Green permits: Distribution by innovation type. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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[17] In additions, green licenses allow no more than three medicinal delousing treatments per production cycle.

[18] Deliotte, 20 May 2019. Evaluation of aquaculture permits for salmon and rainbow trout, Ministry of commerce and fisheries.

[19] Figs. 5, 6, and 7 is based on official statistics and data from the Norwegian Fisheries Directorate, which specify the amount of production permits (each permit allows the fish farmer to produce as set amount of biomass) and the type of innovations/technologies applied to each permit.

[20] Examples include Aquatraz, the Egg, AquaDesign and Hydra Salmon (closed technology), Atlantis Subsea (subsea technology), Havfarm, Havmerd, Arctic Offshore Farming (offshore technology). https://www.fiskeridir.no/Akvakultur/Tildeling-og-tillatelser/Saertillatelser/Utviklingstillatelser/Kunnskap-fra-utviklingsprosjektene.

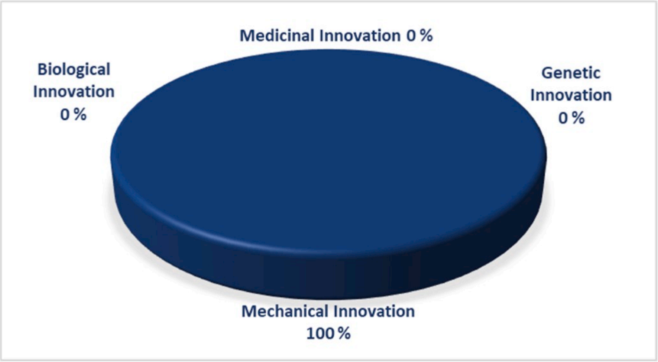

Fig. 7. Development permits: Distribution by innovation type.

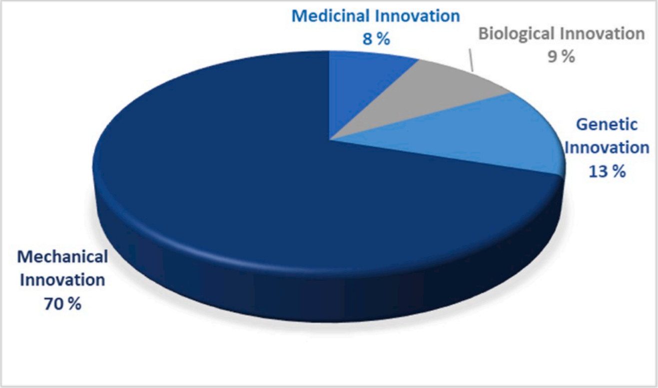

Fig. 8. All permits, 2012–2019: Distribution by innovation type.

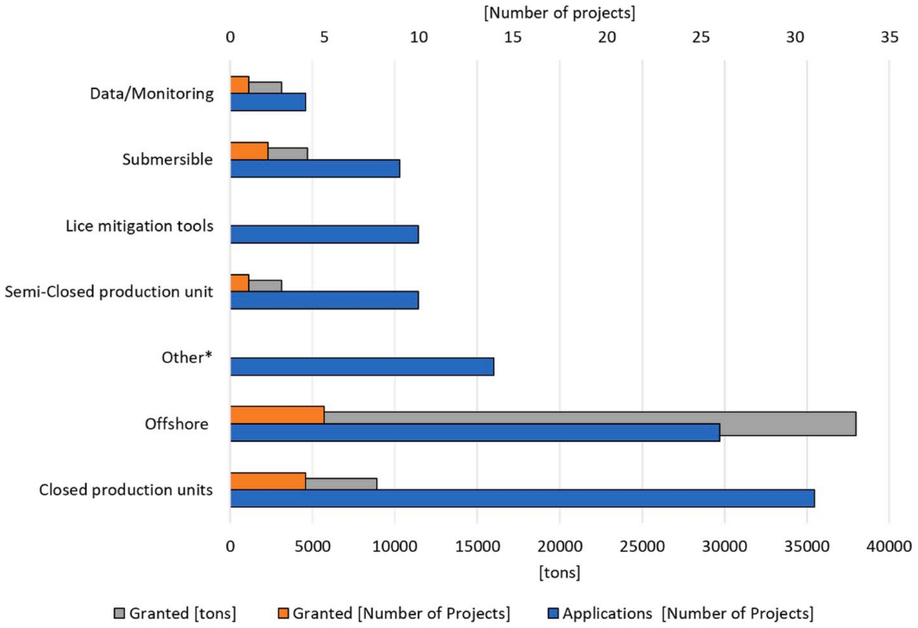

Fig. 9. Development permits: Distribution of biomass by project type.

makes them a potentially attractive investment. However, they do not contribute to lowering sea-lice levels in existing farming areas or lessening the sea-lice infection pressure on wild stocks. Therefore, we argue that offshore fish production technologies are primarily profit-enhancing innovations with a *private good* character. Closed-cage production, on the other hand, has *both* a public and private good character, as closed cages can replace open nets in existing farming areas, provide increased protection against lice, escapement and disease for the firm—while also lowering the sea-lice infection pressure for neighboring, open-net farms, and the surrounding wild populations. That the Norwegian government should prioritize subsidizing offshore over closed-pen technology seems questionable since one would expect the private incentives for investing in offshore technology to be sufficient. Furthermore, as discussed in Section 4.3, this is less likely to be the case for closed cage technology.

There is also a conspicuous lack of regulatory standards and financial support to the development of a more lice-resistant salmon—even though this type of genetic breeding represents a radical, environmental innovation with a public good character—which, as we have shown, calls for strong government intervention. The low amount of genetic innovation activity linked to new permits, in comparison to the activity on mechanical innovation, is also notable.[21] As mentioned, breeding companies have reported highly promising test results in recent years, but there have been few signs of demonstration or early adoption in the market. One might question why the government has not followed up the possibility of imposing legal requirements on breeders to prioritize lice resistance as a genetic trait (as has been done for farmers and sea-lice levels), nor provided some form of risk-reduction through financial support for early adopters (as has been done for mechanical innovation through development licenses).

5.1. *The effectiveness of environmental innovation policy*

Our discussion has shown that new, innovation-geared permits that set stricter standards and provide financial support through permit discounts and opportunities for conversion to commercial permits have triggered substantial radical innovation, especially of the mechanical type. However, the government has prioritized private-good, offshore installations over closed-cage production technology with a public good character, and has failed to address the potential for stimulating

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[21] Producer demand for more lice-resistant roe is known to have surpassed breeders' supply (in 2016 demand was 6 million, supply 3 million), showing that the level of genetic innovation activity has been too low.

progress on genetic breeding for a more lice-resistant salmon.

Insofar as genetic innovation represents a game of "chicken"—where it does not pay to be a sole adaptor and where public benefits outweigh private benefits—strong government intervention may be needed to ensure early adoption and market penetration of a more lice-resistant salmon. One option would be to use the broodstock permit arrangement, which has focused solely on stimulating the development of high-quality salmon roe, to target this type of innovation. New broodstock permits could be issued, free of charge, with legal requirements for breeders to prioritize lice-resistance as a genetic trait. That would also parallel what the government has done for fish-diseases such as ILA, IPN and PD (through making vaccination mandatory).[22] Issuing free broodstock permits that simultaneously allow for commercial salmon production also mirrors the development permit arrangement.

The prioritization of offshore projects does not speak to the overarching goal of the development permit arrangement, the "traffic-light system," and Norway's environmental policy on fish farming more broadly: to reduce sea-lice levels in existing localities, and lower the infection pressure on wild salmonid stocks in the most vulnerable and threatened areas. It also ignores the key policy-innovation need identified in this study: to focus state financial support on environmental innovations with a strong "public good" character.

Yet another problematic element of the development permit arrangement is its lack of focus on pushing the innovations from full-scale demonstration, towards market penetration. We have modelled the innovation processes as consisting of three or more distinct stages: In the first stage (R&D), promising ideas are developed and tested by experimenting in real-world conditions on a small scale. Only some innovations progress to the next stage: full-scale demonstration. Here, we often see early adoption of the most successful prototypes by private actors. Development permits target the early adoption stage, by providing financial support and thus risk-reduction for companies to move ahead with full-scale demonstrations. Yet, the goal of all innovations is to reach the final, market-diffusion stage. For most innovations, this is the stage at which the innovator stands to recover investments made in the previous stages. For environmental innovations, however, broad adoption and use of the technology by a large (er) number of actors also represents crucial step towards goal attainment and achieving measurable environmental improvements.

However, the potential for many of the supported production technologies to diffuse successfully in the market appears questionable. The investment costs (cap ex) for offshore technologies are particularly high compared to traditional, open-net cages. For example, Mariculture's offshore farm had an estimated cap ex of $180 million and Nordlaks's "Havfarm" $120 million; Salmar's "Oceanfarm" was estimated at $86 million. In comparison, the investment cost of 10 traditional open-pen fish farms is about $10 million. The cap ex for closed-cage production installations is, however, somewhat lower: Mowi's "Egg" and "Donut" were estimated at $40 and $50 million respectively, while Akvadesign's closed pen cost NOK 18 million. Less is known about production costs. Many in the industry argue that the increases in production costs for open-net pens due to the need for increased delousing action, will make more expensive production technologies with a higher cap ex and plausibly also op ex, economically feasible. However, this appears to be a matter of speculation.

In a market characterized by stagnation and high demand for growth through new permits, with no requirements for firms to use the technology after project completion, and where development permits may be converted to commercial permits worth $19 million in the market for as little as $1250—all this creates a strong incentive for firms to develop overly expensive solutions that are economically unviable without subsidies. Development permits may even result in "one-off-wonders" that enable winning firms to increase production, but that remain too costly for replication or adoption after project completion, including by other actors for normal, commercial permits. Prioritization of capital-intensive project may result in overly expensive technologies with questionable potential for market penetration.

To the extent that some offshore production technologies become commercially viable, their diffusion might also threaten the global market position of traditional fish farming in sheltered marine environments. Ideas for new production technologies have already been adopted elsewhere, such as the Salmar-inspired "Deep Blue" offshore pen which is used to farm Atlantic salmon in the Yellow Sea—a first attempt at developing a Chinese salmon farming industry.[23] Although sea farming has been the focus of Norwegian government policy, land-based farming technology has also emerged as a promising alternative. While the average production costs of open-net farming continue to increase, projected land-based production costs are decreasing, increasingly bridging the cost-gap, also due to lower transportation costs when located near to end-markets [29]. Thus, radical mechanical innovation may incentivize production in new countries where salmon farming was previously unfeasible, threatening the global position of major salmon-producing countries like Norway.

6. Conclusion

This article has provided an analytical framework that shows how radical environmental innovations with a "public good" character are least likely to be adopted, unless they are backed by targeted government intervention. There are two main types of radical environmental innovation with a "public good" character in aquaculture: in-shore, closed-cage production technology, and the relatively quick introduction of lice-resistance as a breeding goal for salmon. These types of innovation would be in line with the objectives and rationale underlying Norway's stated policy goals. They are also less likely to undermine the traditional objective of Norwegian aquaculture to support regional and local value creation, based on the natural qualities of the fjords, and access to a wide variety of genetic resources from wild Atlantic salmon.

Closer examination, however, shows that these two types of innovation have been less prioritized, if at all, in recent policy interventions. First, a major focus has been on offshore innovation projects, although inshore projects would be better suited for accommodating the sea lice challenge, and less likely to have a negative impact on the sector's overall competitiveness based on the natural advantages of Norwegian fjords. Second, this study has shown the need and potential for stimulating sustainable innovation through the genetic route—a point overlooked in Norway's current policy mix.

CRediT authorship contribution statement

Mads Greaker: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Irja Vormedal:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Kristin Rosendal:** Supervision, Methodology, Writing - review & editing.

Acknowledgement

This projected was supported by the Research Council of Norway, grant no. 244407. The authors would like to thank Mari Lie Larsen for excellent research assistence.

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[22] Such policies are common in agriculture, where the breeding of plant varieties with disease and pest resistance is strongly encouraged, to reduce the use of pesticides.

[23] https://www.undercurrentnews.com/2019/02/18/chinese-firm-to-build-second-offshore-salmon-pen-in-2019/.

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