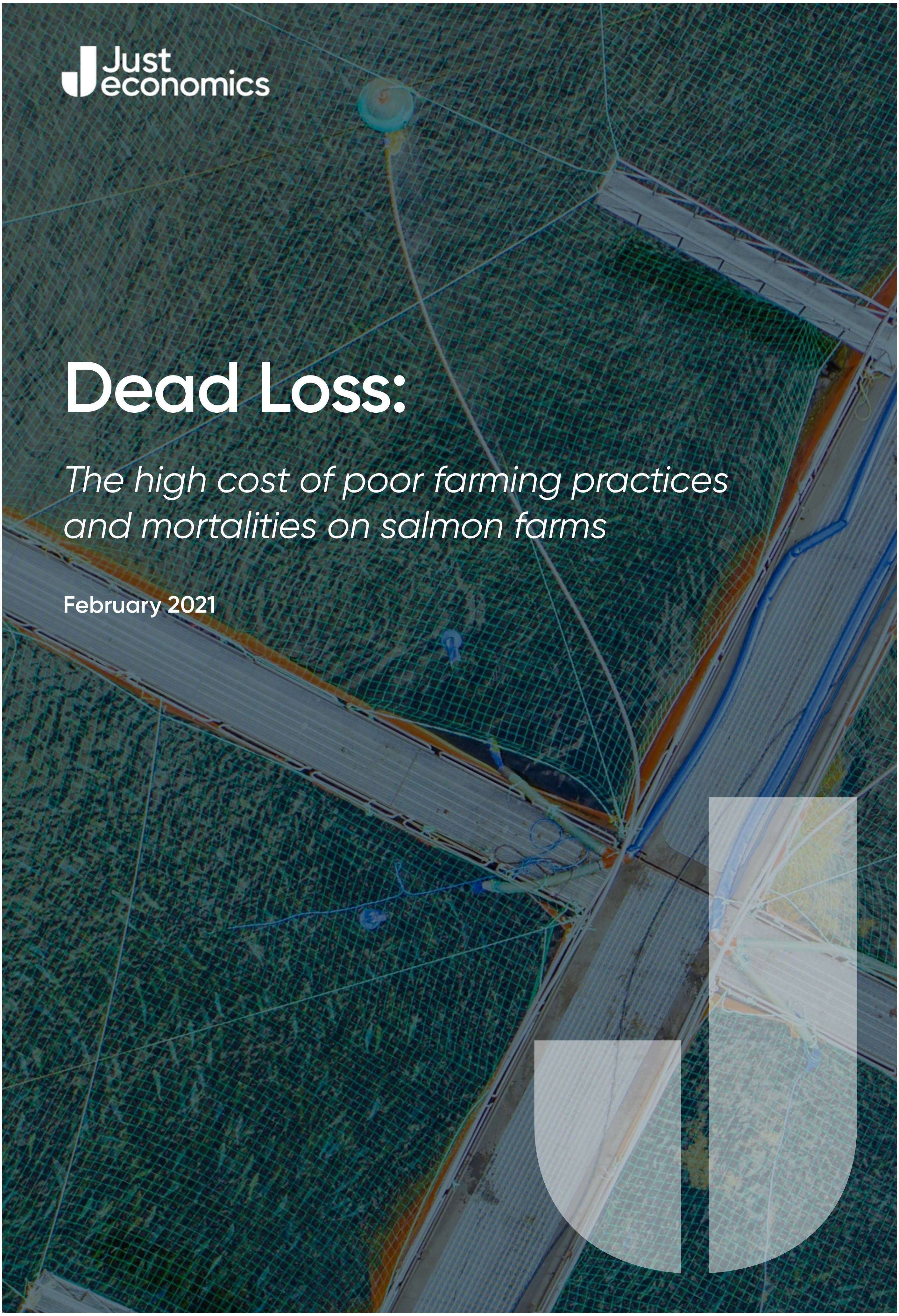

Just economics

Dead Loss:

The high cost of poor farming practices and mortalities on salmon farms

February 2021

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Abbreviations

CO^2 – carbon dioxide

CV – contingent valuation

DHC – direct human consumption

EU – European Union

FAO – Food and Agriculture Organisation of the United Nations

FIFO – Fish In Fish Out

FM – fish meal

FO – fish oil

GDP – Gross Domestic Product

GVP – Gross Value Added

IMTA – Integrated Multi Trophic Aquaculture

ISSF – Inside Scottish Salmon Feedlots

LCA – life cycle analysis

mt – million tonnes

MUSD – million United States Dollars

NASCO – North Atlantic Salmon Conversation Organisation

NOK – Norwegian kroner

PAC – pollution abatement costs

RAS – Recirculating Aquaculture Systems

SEPA – Scottish Environmental Protection Agency

t – Tonnes

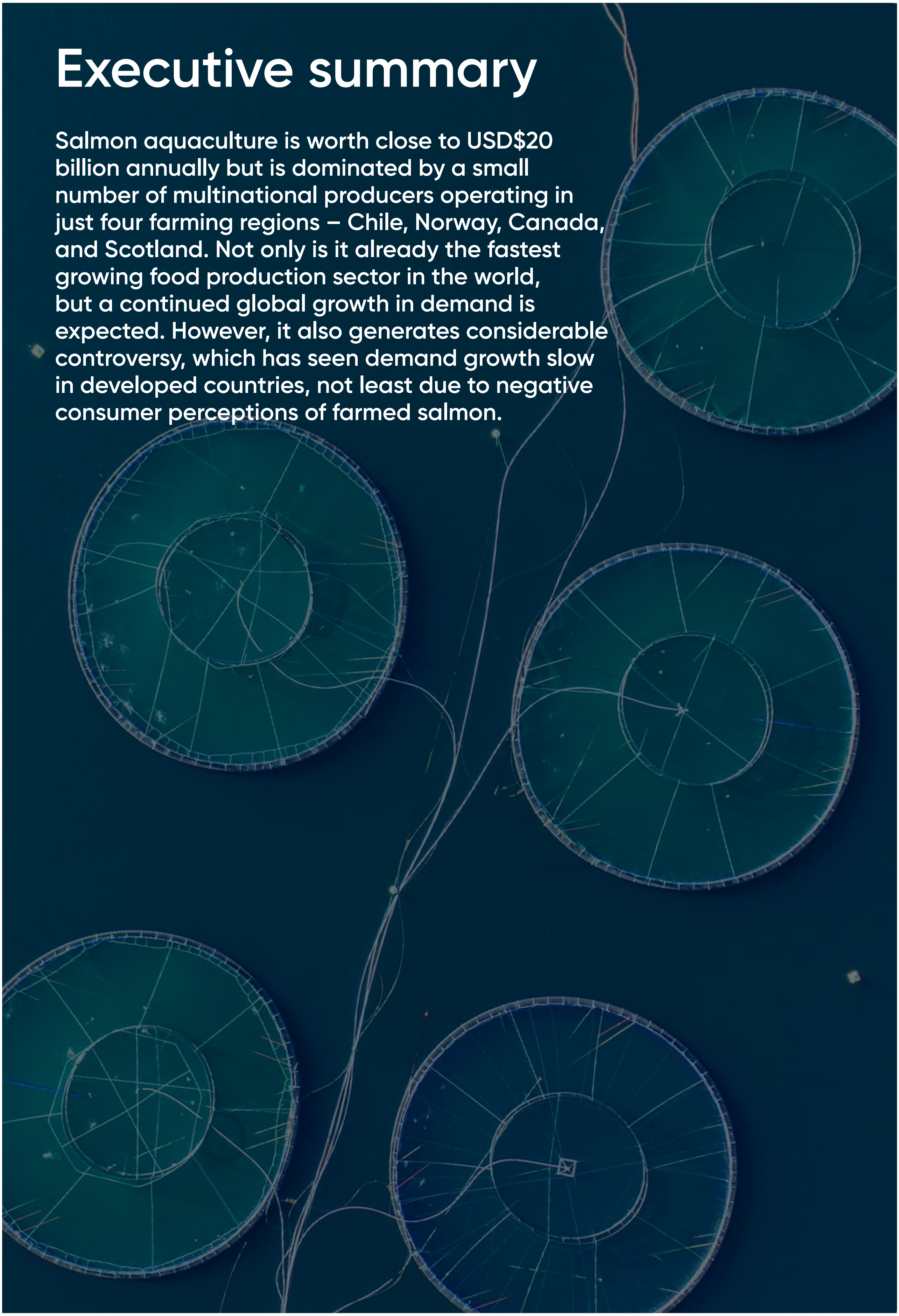
UK – United Kingdom

USD – United States Dollars

WTP – willingness to pay

Executive summary

Salmon aquaculture is worth close to USD$20 billion annually but is dominated by a small number of multinational producers operating in just four farming regions – Chile, Norway, Canada, and Scotland. Not only is it already the fastest growing food production sector in the world, but a continued global growth in demand is expected. However, it also generates considerable controversy, which has seen demand growth slow in developed countries, not least due to negative consumer perceptions of farmed salmon.



Although the big four producing countries all have ambitious plans for growth, these are endangered by economic, environmental, and regulatory pressures. Governments in these countries are largely uncritical of their salmon farming industries, and official literature tends to promote a positive image. A typical narrative is that of a clean and healthy source of protein that is helping to revive coastal communities. Beneath the marketing discourse, however, transparency and accountability are extremely weak by comparison with land-based farming. Data are often absent on important phenomena such as mortalities, escapes and environmental impacts. The sector lacks robust regulation and proper social, environmental, and economic accounting, which makes it difficult to assess its impacts holistically.

The report has two aims therefore:

- To highlight the unnecessary costs borne by the salmon industry because of poor fish husbandry and welfare and to estimate potential savings from improved farming practices; and
- To estimate the social and environmental costs of the salmon industry and to estimate the value to consumers and wider society of reducing those costs by improving social and environmental performance.

The study was commissioned by the Changing Markets Foundation as part of its Fishing the Feed campaign. The research was carried out independently by Just Economics.

Aquaculture is a diverse farming practice, and we acknowledge that it can make a positive contribution to food security and livelihoods. However, as the research highlights, there are significant problems with the highly industrialised, intensive form that salmon farming currently takes. The aim of this report is to draw attention to these issues by placing financial values on the costs they incur to highlight their scale and importance.

The report focuses on the four big producing countries (which account for 96% of farmed salmon production) and the top ten producers globally (which account for 50% of production). In conducting the research, we encountered significant data limitations. Table 1 lists the variables that were included and excluded (although for the producer analysis data were only available on two variables: salmon mortality and lice fighting technologies). Decisions to exclude variables were based on data availability, rather than importance, and future research should seek to address these data gaps.

Table 1: Variables included and not included in country level analysis

Cost category	Variables included	Variables not included
Economic	Salmon mortality Use of marine ingredients in feed Use of lice fighting technologies	Costs of pesticides and medicines Loss of tourism/eco-tourism income Costs of cleaner fish
Social	Salmon welfare Economic impacts of fish use in aquafeed	Cleaner fish welfare Health/social impacts of use of fish in aquafeed Health impacts of antibiotic and pesticide use
Environmental	Depletion of wild salmon stocks Partial biodiversity loss due to depletion of pelagic fish stocks Impacts of local pollution Climate change impacts	Full biodiversity impacts of krill, pelagic fish and cleaner fish stock depletion Loss of wild sea trout stocks Environmental impacts of pesticides, antibiotics, and medicine use Impacts of other feed ingredients such as soy

For each variable included, we drew on existing research to estimate incidence for each country/producer and cost. These were modelled for the seven years to 2019 i.e., from the point at which the industry began to expand rapidly. The findings for each variable are discussed in turn, beginning with economic costs.

Economic costs

Mortality rates on salmon farms are high, with parasites (and their treatments), disease (and their treatments), pollution and escapes being the major contributing factors. Although some mortalities are inevitable, the rates have increased dramatically in recent years and far outstrip those found in other forms of intensive farming. The factors that induce mortality are often directly related to the quality of fish husbandry, and mortality could therefore be considered an indication (and cost) of poor farming practices. Mortalities data are only available for Norway and Scotland. The combined cost since 2013 of mortalities in these two countries is estimated at USD$9.8 billion (8.9 billion in Norway and almost 922 million in Scotland). If we apply the average mortalities for these two countries to Canada and Chile, we get an estimate of USD$768 million and $4.9 billion respectively. Using this methodology, the total cost across the four countries is USD$15.5 billion, representing a huge opportunity cost for farmers. The analysis also shows that reducing mortalities to 5.5% - closer to mortality rates on egg-laying hen farms - in Norway would represent an annual saving of over $892 million USD (based on 2019 volumes and prices).

Even when parasites and disease do not result in deaths, their treatment is costly, and the presence of lice in particular is a barrier to sector expansion. There are also clear consumer concerns about the use of medicines and chemicals to control them. Lice and disease spread are hastened by high stocking densities which are designed to increase the productivity of farms. However, this is arguably a false economy. Estimates of the cost of controlling lice alone is between 6 and 8.5% of the cost of production. Using these data, we estimate a cost to the sector from lice control of over $4 billion since 2013.

Aquafeed is the single largest cost centre for salmon farmers with much of this being driven by the high cost of fish meal (FM) and fish oil (FO), which are derived from wild fish. We estimate that the cumulative costs of using marine ingredients in salmon farming is over $8 billion in the four countries over the period (2013-2019).

We can also apply these estimates to the top ten producers, which had combined total revenues of USD$12 billion dollars in 2018. By comparing the expected and actual harvest for these companies since 2010 (Table 2), we can see that between them they were responsible for the loss – through mortalities and escapes - of over half a million tonnes of salmon during this period (or about 100 million salmon). This equates to almost USD$3.7 billion. In about 70% of cases the cause of mortality is either not known, or not disclosed. For the remaining 30%, the leading cause is sea lice, followed by disease and algal blooms (as a result of pollutants). Using a global estimate of 6% for the cost of combatting sea lice, allows us to estimate a cost for these companies (UDS$3.5 billion since 2013).[1] This gives a combined cost of mortalities and lice treatment of USD$7.1 billion or 12% of revenues over the period.

Table 2: Estimated mortalities and associated losses by producer (2010-2019)

Company	Volume of losses (tonnes)	Cost (MUSD)
Seafood Mowi	252521	$1,719
Leroy Seafood	66975	$456
Grieg Seafood	64992	$442
Australis	34042	$231
Blumar	32236	$219
Norway Royal Salmon	28342	$193
Bakkafrost	21058	$143
Salmar	15929	$108
Camanchaca	11550	$78
Seafood Invermar	9256	$63
Total	**536901**	**$3,656**

Environmental costs

Salmon farming is generating and running up against several environmental pressures, which are inextricably linked to its commercial success, and these are a major source of risk for the industry. Atlantic salmon can only be farmed under certain conditions and as seas warm and available locations become exploited, the industry is running out of viable sites for new farms. This means that new sources of growth are dwindling, creating pressure to locate farms in less suitable environments and to increase stocking densities, which further exacerbate environmental pressures.

1 In the previous section, we report that the lice control estimates for the four countries is $4bn. These were developed from lice treatment costs per kg. whereas this figure derives from a percentage of revenue. As discussed in the main body of the report, the country-level analysis most likely underestimates the cost of lice.

Aquaculture activities are an interconnected part of the ecosystem in which they exist, and salmon farms make use of 'free' coastal ecosystem services such as clean water, appropriate temperatures, nutrient levels and so on. They also contribute to their deterioration, however, due to local pollution impacts from uneaten feed and faeces, which are directly discharged into the marine environment. The Pollution Abatement Cost (PAC) measures the amount that would be required to preserve or restore a unit of an environmental good. Unless the full PAC is accounted for, salmon farms are 'free riding' on these environmental services. A PAC has been calculated for Norwegian salmon farming. Although one of the best environmental performers of the countries included here, this still amounts to an economic cost of 3.5% of total production. When this is applied across the four countries, it gives us a total cost of over USD$4 billion since 2013.

Salmon farming is also impacting negatively on wild fish stocks. There are three ways in which this manifests: damage to wild salmon stocks, the use of pelagic fish in FMFO, and the use of cleaner fish in parasite control.

There have been serious concerns about the status of wild Atlantic salmon stocks for many years now, and the numbers of returning salmon are at an all-time low. Several studies have reviewed the social, economic, and cultural value of the Atlantic salmon, which has an iconic status within communities along the Atlantic seaboard. This value can be observed in contingent valuation studies that show high 'Willingness to Pay' (WTP) amongst households to protect and restore wild salmon stocks. Although the reasons for declining salmon stocks are many and varied, it is widely believed that salmon farming is a contributing factor. Farms spread lice and disease to wild populations and pollute local areas through which returning salmon will sometimes pass. Escaped farmed salmon also hybridise with wild populations and reduce their ability to survive in the wild. Our economic analysis of the loss of salmon stocks attributable to salmon farms is focused on Canada, Norway, and Scotland where the contingent valuation studies have been carried out. We find the value destroyed by salmon farming through loss of wild stocks to be USD$308 million.

Pelagic fish are highly nutritious forage fish and are the main fish source used in the production of FMFO used in salmon feed. Almost one-fifth of the world's annual wild fish catch is taken out of the ocean for this purpose, the majority of which is used in seafood farming. However, (in addition to being a key source of protein for many coastal communities) forage fish also play a central role in the ecosystem as they are the primary food source for many marine mammals, seabirds, and larger fish; and some species such as sardinella in West Africa are now heavily overfished. Valuing their role in the ecosystem is extremely complex but just considering their contribution to the commercial catch of carnivorous species gives us an additional 'hidden' value of $219 per tonne. Applying this to FMFO use in our four countries gives us an indication of the ecosystem value of forage fish lost to fish farming (USD$1.78 billion over the seven years). Data suggest that the removal of wild fish from feed formulations has plateaued; if this is the case, we would expect to see these costs rise considerably in line with the expansion of production that is planned in all of the countries studied (a fivefold increase in Norway by 2050 and a doubling in Scotland by 2030 to give just two examples).

Compared with salmon, there is limited research on cleaner fish, and their biodiversity impacts and welfare are only discussed in a limited way in the literature. More research is required therefore to fully account for the impacts of salmon farming on wild fish populations.

Finally, we consider climate change impacts. Aquaculture is often positioned as a low carbon alternative to land-based farming, and whilst the farmgate emissions are low relative to agriculture it is argued that these figures underestimate the true carbon cost once feed and airfreight are taken into consideration. Life Cycle Analysis (LCA) provides a more complete estimate of carbon emissions because it includes impacts throughout the supply chain. LCA of carbon emissions across producer countries shows that Norway has the lowest impacts, whereas impacts are consistently highest in Scotland. However, due to data limitations, we have applied the Norwegian LCA estimates to the four countries. This analysis reveals that the minimum social cost of carbon from salmon farming in the four countries is almost USD$8.3 billion during the timeframe studied.

Social issues

The main social issue included in this report is the impact on salmon welfare. As we have seen, farm profitability and salmon welfare are inextricably linked. In the short-term there may be a financial incentive to take shortcuts with fish husbandry but over time these lead to disease, lice, stress and ultimately higher mortality rates, which also result in financial losses. It is therefore in the long-term interests of farms to keep densities at the optimum level for fish health and welfare, and to adopt the highest farming standards. Moreover, there are strong, and growing consumer preferences for high fish welfare. especially in Europe. A European study finds that the average European consumer would be willing to pay 14% more for salmon with higher welfare standards. If we apply this to European and Canadian consumers of salmon (where attitudes are similar) we get a value of $4.6 billion.[2]

The final cost considered is the impact of diverting forage fish away from direct human consumption (DHC) in low and middle-income countries for use in the FMFO industry, in large part to feed European aquaculture. Countries such as those along the West African seaboard have significant food security issues. In addition, the growth of the FMFO industry may lead to net economic losses because of the loss of jobs in traditional fishing and food preparation (especially for women). Finally, as already discussed, these waters are already heavily fished and further declines in the catch will disproportionately affect local fishing communities. Data limitations mean it was difficult to value these financial losses. However, a case study for Norway, which imported 8.4 thousand tonnes of fish oil from Mauritania in 2018 shows a loss to Mauritania in 2019 of USD$37.5 million.

Conclusions and recommendations

The demand for seafood is expected to increase in coming years and part of this will have to be met by increased aquaculture production. Fish farming has the potential therefore to be a significant source of social, economic, and environmental value but farming practices matter greatly and determine whether the industry can be considered a net loss or net benefit to society. Although we encountered significant data gaps, this analysis has allowed us to place a value on some of the costs of salmon farming as currently practiced. It suggests that salmon aquaculture has produced private and external costs of USD$47 billion since 2013 (see Table 3 for a summary of these). When we segment these into private and external costs, we can see that around 60% fall to producers and 40% to wider society (USD$28 billion and USD$19 billion respectively).

2 Studies of welfare tend to be conducted amongst consumers rather than producer citizens and the calculations have been focused on these consumers where data are available and animal welfare issues are most salient.

Table 3: Summary of costs for each variable by country (MUSD)

	Canada	Norway	Chile	Scotland	Total
Mortalities	768	8908	4939	922	15,539
Lice	111	2142	1647	463	4,365
FMFO	454	4832	2045	859	8,192
Total economic cost	**1333**	**15969**	**8631**	**2233**	**28,096**
Salmon stocks	*187*	*52*	Insufficient data	*68*	308
Pelagic fish stocks	*135*	*665*	302	*680*	1,784
Local pollution	189	2328	1268	*288*	4,073
Climate change	*425*	*5224*	2282	*425*	8,356
Total environmental cost	**936**	**8269**	**3852**	**1461**	**14,521**
Fish welfare	*97*	*3675*	Insufficient data	*902*	4,674
Total social cost	**97**	**3675**	Insufficient data	**902**	**4,674**
Total	**2366**	**27913**	**13304**	**4596**	**47,291**

Considering the full range of costs and benefits may well demonstrate positive benefits from aquaculture (and even salmon farming). Yet what this report shows is that there are substantial costs that are not currently included on the balance sheet and that the scope for improved environmental and social performance is considerable. In addition, a combination of growing environmental impacts, consumer demand for ethical and environmentally friendly products and direct losses from poor fish husbandry are creating long run economic risks to the industry, that can only be mitigated by investing in better farming practices and reduction of environmentally harmful aspects, such as use of wild-caught fish.

Our recommendations focus on the four most significant stakeholders in salmon farming: governments, investors, farmers and consumers, each of which has a role to play in transitioning to a more sustainable aquaculture and food system.

For governments

Economic benefits of salmon farming need to be balanced against other coastal industries such as tourism, angling and wider environmental impacts. Governments should be prepared to support alternative technologies that improve social and environmental standards, as these are likely to be net beneficial in the long run.

Better oversight and more robust regulation of salmon farming should lead over time to competitive advantage as consumers increasingly seek out more ethical and environmentally friendly products. Governments can lead the way on this by restricting licences to companies that meet higher social and environmental standards.

The industry would benefit from guidelines for sustainable feed ingredients along with stricter due diligence and governance frameworks in aquafeed supply chains. Governments should also support the phase-out of whole wild-caught fish for use in aquafeed. Furthermore, aquaculture that relies on wild-caught fish should not receive any subsidies or other public support measures. Policy should support the development of alternative technologies (for feedstuffs and farming methods) and provide effective economic incentives.

Governments should also require more transparent reporting in this industry and should resist industry pressure not to publish mortalities data that are in the public interest. In addition, consumers increasingly expect transparency in supply chains and companies/sectors which fail to respond to that expectation will place themselves at a disadvantage in the market.

More generally there is a need to improve the quality of social, economic, and environmental accounting in salmon farming. This would have the dual benefit of supporting more holistic decision-making and incentivising better farming practices. By revealing costs and benefits, governments could create a race to the top amongst salmon farmers, and a level playing field for small producers that may be operating to higher standards. At a minimum, governments (e.g. in Scotland) should refrain from making a priori economic arguments in favour of salmon farming, given the narrowness of these arguments and their responsibilities to a wider group of stakeholders.

For investors

As a result of growing environmental and regulatory pressures, investment decisions are required that drive a rapid transition towards alternative feeds and better farming practices. These already exist but require more investment to make them viable in the short-term.

Although the risks of existing farming practices are often understood, investors continue to support them due to short-term returns. This creates a barrier to the adoption of new technologies and improved practices, and investors need to take a long-term view. This may involve accepting lower returns in the short term but as discussed in this paper issues with both supply and demand should create competitive advantage in the long run.

For farmers

Mortalities, lice treatments and disease are creating huge costs for farmers and damaging the reputation of farmed salmon. Significant opportunities exist to dramatically improve the environmental and social performance of salmon production through a focus on the development of least-environmental cost (as opposed to least-economic-cost) feed formulations. These technologies exist - and have been shown to work - and producers could appeal to the growing consumer demand for an ethical product by being early adopters of these formulations. As the cost of marine ingredients is expected to increase, these may also prove to be a lower cost alternative in the medium term.

As demonstrated in this report, poor fish husbandry is a false economy as it leads to significant direct and indirect costs. We recommend therefore that farmers adopt better husbandry, such as stocking densities commensurate with higher survival rates.

For consumers

Salmon was once a high value food that was only available in season and consumed on special occasions. In line with the need for investment from all stakeholders, some consumers should also be prepared to pay more for salmon where their economic circumstances allow, and/or to consume it less frequently. As part of this, consumers could seek out alternatives to carnivorous fish such as molluscs that provide dietary and economic benefits at lower social, economic, and environmental costs.

The false economy of poor farming practices on salmon farms

Salmon aquaculture is worth close to

US **$20 billion**

annually with **96%** of production concentrated in just four countries.

CANADA | NORWAY | CHILE | SCOTLAND

and **50%** of production controlled by **10 multinational companies.**

Mortality rates on salmon farms are high with the major contributing factors being:

PARASITES

ESCAPES

POLLUTION

DISEASE

Estimated cost of mortalities is

$15.5 billion

with the top 10 producers responsible for 100 million salmon deaths and escapes since 2013.

Lice and disease spread are a result of high stocking densities designed to increase productivity. This is arguably a false economy: since 2013 lice control alone has cost the sector over

$4 billion

Aquafeed is the single largest cost centre for salmon farmers, driven by the high cost of fishmeal and fish oil (FMFO), derived from wild fish. We estimate over the period 2013-2019 that the cumulative costs of using marine ingredients in salmon farming is over

$8 billion

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$4 billion

is the estimated cost of pollution for the four countries since 2013. Pollutants from salmon aquaculture include **uneaten feed and faeces**, which are directly discharged into the marine environment.

Salmon farming is also contributing to the decline of wild salmon through

LICE & DISEASE SPREAD **POLLUTION** **HYBRIDISATION**

Yet there is a strong 'willingness to pay' amongst consumers in the four countries to preserve wild salmon. As a result we estimate a loss to communities of

$308 million since 2013

A partial valuation of the ecosystem benefits of forage fish lost to fish farming, due to the use of **FMFO**, is around

$1.8 billion

Consumers in **Europe and Canada** have shown a high willingness to pay for better fish welfare. We estimate the cost of poor fish welfare at

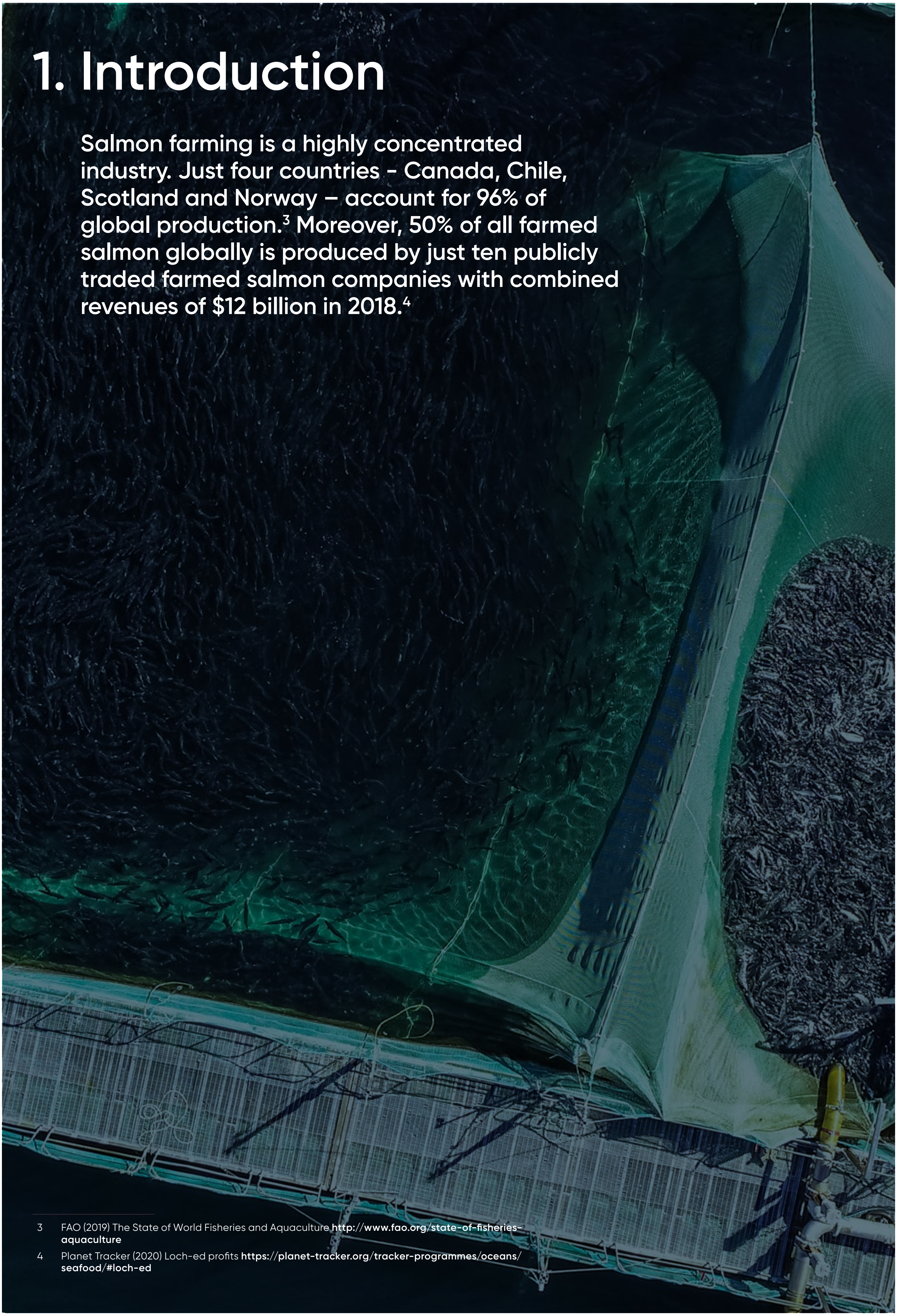
$4.6 billion

$8.3 billion

Is the estimated social cost of carbon from salmon farming. Although positioned as a low carbon alternative to meat, life cycle analysis reveals a higher cost than reported

Since 2013 the unaccounted cost of salmon farming across the four countries is over

$47 billion



1. Introduction

Salmon farming is a highly concentrated industry. Just four countries - Canada, Chile, Scotland and Norway – account for 96% of global production.[3] Moreover, 50% of all farmed salmon globally is produced by just ten publicly traded farmed salmon companies with combined revenues of $12 billion in 2018.[4]

3 FAO (2019) The State of World Fisheries and Aquaculture **http://www.fao.org/state-of-fisheries-aquaculture**

4 Planet Tracker (2020) Loch-ed profits **https://planet-tracker.org/tracker-programmes/oceans/seafood/#loch-ed**

Historically, salmon farming has been a highly profitable industry, so much so that salmon has become the largest single fish by commodity value.[5] Between 2012 and 2016 salmon stock prices appreciated by 43.5% per year.[6] Consumer demand is also expected to grow in both developed and developing markets in the coming years.[7] More recently, however, the industry is encountering economic, environmental, and regulatory pressures that endanger future growth. After years of remarkable financial performance, productivity growth has slowed, and market risks have increased. These have been compounded in 2020 by the Covid-19 pandemic, which has seen the price of salmon slump due to oversupply.[8]

Aquaculture lacks proper social and environmental reporting, which could improve decisions about where, when and under what conditions salmon farming is desirable.[9] In its absence, salmon farmers are incentivised to pursue short-run commercial ends,[10] which create long-run economic, social and environmental risks.[11] Some of these are direct costs from poor fish welfare (e.g. mortalities resulting from poor fish husbandry or damaged consumer demand), whereas others are indirect such as pollution-induced mortalities of farmed fish. These will ultimately increase the cost of doing business and most likely impact on consumer preferences for farmed salmon, both of which will affect the future profitability of the sector.

The aim of this report is to address the limitations in reporting by estimating the private and external costs of the industry. The research is scoped to only consider salmon farming and associated costs. We acknowledge that wider aquaculture has many positive impacts, especially in low-income countries where research finds positive impacts on livelihoods and food security.[12] Salmon farming has also been found to generate public and private benefits. These include consumer and producer surplus. Consumer surplus refers to the benefits of being able to purchase cheaper salmon (which is an important - albeit not the only - source of omega 3 oils and animal proteins), and producer surplus to the profits made by producers. There are also benefits to governments through tax transfers and local communities, which receive some benefit from industry and employment.

However, there are large number of stakeholders affected by salmon farming and each group/entity bears different costs and benefits. Economic analyses are often conducted from the perspective of a limited number of stakeholders (e.g., focusing on employment benefits[13] but excluding costs borne by other coastal stakeholders).[14] To counter this, this study focuses largely on the costs that have often been excluded from economic analyses to date.

5 Ibid.

6 Misund, B., & Nygård, R. (2018). Big fish: Valuation of the world's largest salmon farming companies. Marine Resource Economics, 33(3), 245-261.

7 Gephart, J. A., Golden, C. D., Asche, F., Belton, B., Brugere, C., Froehlich, H. E., ... & Klinger, D. H. (2020). Scenarios for global aquaculture and its role in human nutrition. *Reviews in Fisheries Science & Aquaculture*, 1-17.

8 Intrafish (2020) Larger sizes cause salmon prices to plunge again amid COVID-19 impacts **https://www.intrafish.com/coronavirus/covid-19-live-farmed-salmon-prices-plunge-again-alaska-pollock-gets-a-lift-beijing-issues-warning/2-1-746616**

9 Georgakopoulos, G., & Thomson, I. (2005, March). Organic salmon farming: risk perceptions, decision heuristics and the absence of environmental accounting. In Accounting Forum (Vol. 29, No. 1, pp. 49-75). No longer published by Elsevier.

10 Aanesen, M., & Mikkelsen, E. (2020). Cost-benefit analysis of aquaculture expansion in Arctic Norway. Aquaculture Economics & Management, 24(1), 20-42.

11 Taranger, G. L., Karlsen, Ø., Bannister, R. J., Glover, K. A., Husa, V., Karlsbakk, E., ... & Madhun, A. S. (2015). Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. ICES Journal of Marine Science, 72(3), 997-1021.

12 Béné, C., Arthur, R., Norbury, H., Allison, E. H., Beveridge, M., Bush, S., ... & Thilsted, S. H. (2016). Contribution of fisheries and aquaculture to food security and poverty reduction: assessing the current evidence. World Development, 79, 177-196.

13 Riddington G. Radford A. and Gibson H (2020) The Economic Contribution of Open Cage Salmon Aquaculture to Scotland: A Review of the Available Economic Evidence **https://www.salmon-trout.org/wp-content/uploads/2020/04/Riddington-Radford-Gibson-Economic-Contribution-of-Salmon-Aquaculture-to-Scotland.pdf**

14 Young, N., Brattland, C., Digiovanni, C., Hersoug, B., Johnsen, J. P., Karlsen, K. M.,... Thorarensen, H. (2019). Limitations to growth: Social-ecological challenges to aquaculture development in five wealthy nations. Marine Policy, 104, 216–224.

The report has two aims therefore:

- To highlight to key stakeholders the unnecessary costs borne by the salmon industry because of poor fish husbandry and welfare and to estimate potential savings from improved farming practices; and
- To estimate the wider social and environmental costs of the salmon industry and to estimate the value to consumers and wider society of reducing those costs by improving social and environmental performance.

The study was commissioned by the Changing Markets Foundation as part of its Fishing the Feed campaign. The research was carried out independently by Just Economics.

The report provides a focus on each of the four main producer countries. We begin with a short summary of the issues in salmon farming before going on to describe the methodology. We then discuss each country in turn and conclude with a set of recommendations for investors, governments, farmers and consumers.

2. Methodology

The analysis focuses on the four top salmon producing countries: Norway, Scotland, Chile and Canada as well as the top ten producers. In this section, we describe the overall approach before going on to discuss the limitations and caveats.

2.1 Overall approach

For the country analysis, we have identified the most material economic, social, and environmental costs connected to salmon farming and researched an appropriate data source, or plausible assumption to derive a value for that cost. In many areas, we encountered significant data limitations, and it has not been possible to include all costs in every instance. Table 4 sets out the variables that were included and not included in the country level analysis. Even where it was possible to include a variable in the analysis, we did not always have sufficient data on each country to develop a full estimate. These are detailed below in the summary. A full methodology for each country is available in the appendices.

Table 4: Variables included and not included in country level analysis

Cost category	Variables included	Variables not included
Economic	Fish mortality Use of marine ingredients in feed Use of lice fighting technologies	Costs of pesticides and medicines Loss of tourism/eco-tourism income
Social	Salmon welfare Economic impacts of fish use in aquafeed	Cleaner fish welfare Health/social impacts of use of fish in aquafeed Health impacts of antibiotic and pesticide use
Environmental	Welfare loss of depleted salmon and partial biodiversity loss of pelagic fish stocks Impacts of local pollution Climate change impacts	Full biodiversity impacts of krill, pelagic fish and cleaner fish stock depletion Loss of wild sea trout stocks Environmental impacts of pesticides, antibiotics, and medicine use Impacts of other feed ingredients such as soy

For the top ten producers, data were even less readily available. We focused this analysis therefore solely on two of the most material economic costs: the opportunity cost of fish mortality and the cost of lice fighting technologies.

We also sought, throughout the analysis, to adopt the most conservative assumptions. This, combined with limited data on key variables means that the estimates presented here most likely underestimate the full social, economic and environmental costs of salmon farming. For most of the variables, we have estimated the impacts from 2013 when production began to expand more rapidly and mortality rates began to increase.[15] For example, in Norway mortality increased steadily from 10.9% in 2013 to 14.5% in 2019.[16] A key variable used in the analysis is the price of salmon. Salmon prices will vary considerably by country, producer, brand and so on. These price variations run the risk of masking variations in outcomes (fish husbandry, pollution and so on) between countries. To avoid this, we have standardised the value of salmon across the four countries and

15 Planet Tracker (2020) Loch-ed profits **https://planet-tracker.org/tracker-programmes/oceans/seafood/#loch-ed**

16 Statistics Norway 07516: Fish farming. Loss in fish for food production, by fish species (C) 1993 – 2019 **https://www.ssb.no/en/statbank/table/07516/tableViewLayout1/**

the top producers by using the annual average IMF salmon export price.[17] This allows us to hold the price of salmon constant, which enables more accurate comparisons between countries. However, it may over- or underestimate costs in certain areas.

For each variable, we have estimated the scale of the problem produced by the salmon industry and identified a method of valuing the cost of this impact. For the economic costs, this was relatively straightforward. For example, for mortalities, we have taken annual mortalities since 2013 and multiplied them by the price salmon fetched in that same year. For the environmental costs, we have mainly relied on the findings from studies by environmental economists that have estimated life cycle costs or pollution abatement costs of salmon farms. However, for some variables where studies were not available, we have also generated assumptions, rooted largely in the academic literature. These assumptions have been documented in the discussion below.

Of the three categories of costs, social costs are the most challenging to estimate. In this section, we have mainly relied on stated preference method (SPM). SPM refers to a family of tools and techniques used in cost benefit analysis to estimate the value of non-market-traded goods and services.[18] In general terms, respondents are asked to rank, rate, or choose between different hypothetical scenarios that contain a mix of different attributes. How people value those different attributes – their willingness to pay (WTP) - can then be inferred from the choices they make. Stated preference methods are useful for estimating 'non-use value'. Whereas 'use value' is derived from the consumption of a good or service, non-use value quantifies the benefit we derive from goods or service that we cannot consume.[19] There are different forms of non-use value that are relevant here. These include:

- Existence value - the benefit we derive from knowing that a phenomenon exists, even if we may never directly encounter it (e.g., an endangered species).
- Option value - captures the value we derive from preserving a particular resource base for future generations and
- Bequest value - refers to the value we place on being able to bequeath it to future generations

This approach is especially apposite for valuing phenomena like fish welfare and wild fish stocks, which we know are of significant value to consumers, including those within the top producer countries of Norway, Canada and Scotland.[20]

2.2 Limitations and caveats

The study was limited substantially by data limitations, especially for Chile. In some instances, assumptions had to be used (e.g., extrapolated from other countries). Whilst we always sought to do these in a plausible way, this is always a second-best option. A second limitation is that the analysis only takes account of costs. The study has been scoped as such, but it could be developed in the future into a more holistic cost benefit study. A third caveat is that the study is limited only to salmon, which is already a well-researched type of aquaculture. Aquaculture is a diverse industry involving many kinds of seafood, farmed in different ways by different types of farmers. This ranges from artisanal, family-owned producers in developing countries to industrial-scale farming usually operating transnationally. Although salmon farming is largely dominated by

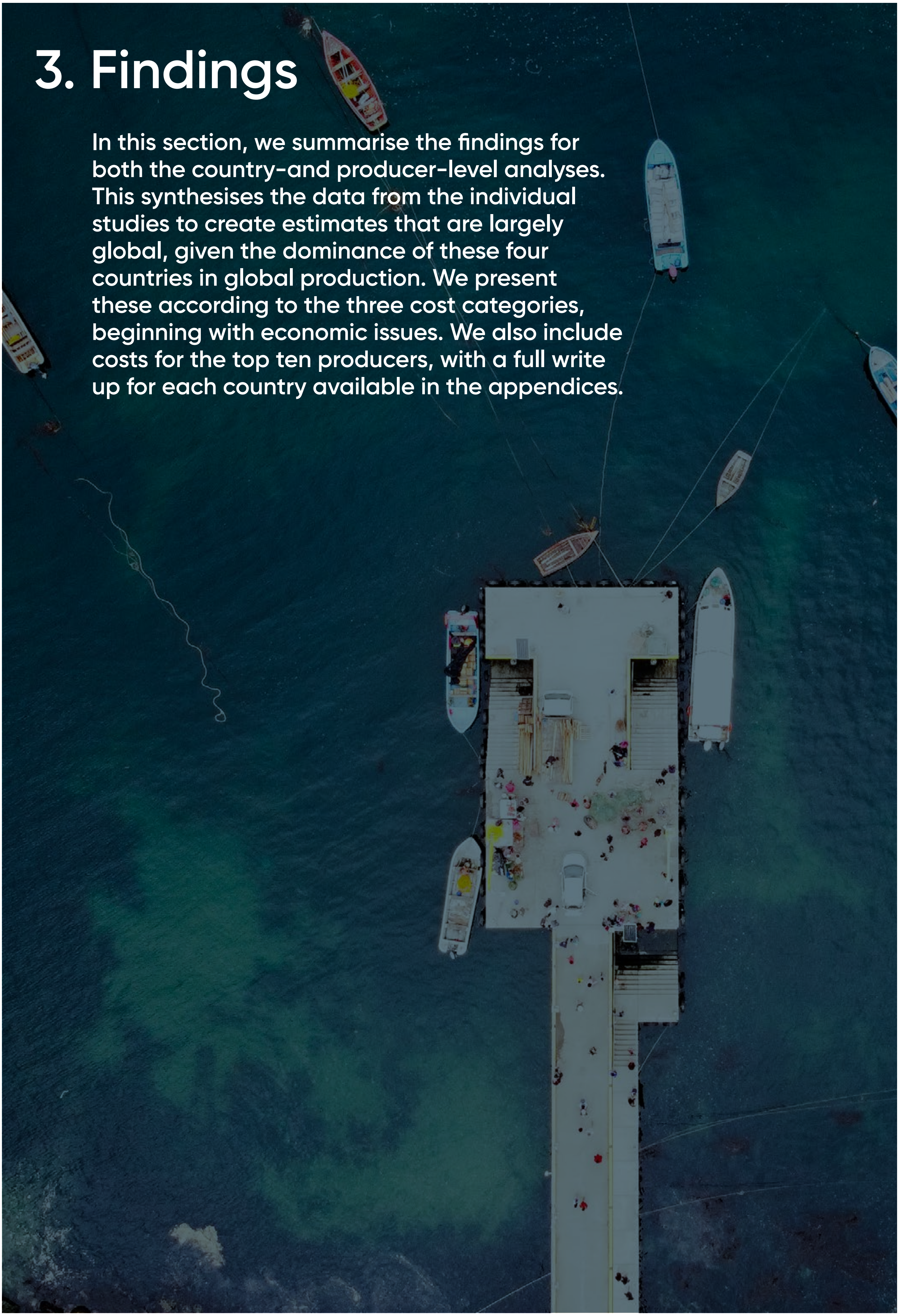
17 https://data.imf.org/?sk=471DDDF8-D8A7-499A-81BA-5B332C01F8B9

18 Carson, Richard T., and W. Michael Hanemann. "Contingent valuation." *Handbook of environmental economics* 2 (2005): 821-936.

19 Pearce, D. W., & Turner, R. K. (1990). *Economics of natural resources and the environment*. JHU press.

20 Riepe, C., Meyerhoff, J., Fujitani, M., Aas, Ø., Radinger, J., Kochalski, S., & Arlinghaus, R. (2019). Managing river fish biodiversity generates substantial economic benefits in four European countries. Environmental management, 63(6), 759-776.

the latter, this is not the case for other species. This study does not therefore draw any wider conclusions about aquaculture more generally. Finally, although the study draws on evidence from alternative technologies and alternative feeds, it does not model the relative costs of using these approaches. The study mostly considers mainstream practice as it has operated over the past seven years. However, the authors acknowledge that there are lots of innovations in the industry many of which have the potential to improve social and environmental outcomes. These will be considered again in the conclusions and recommendations sections.



3. Findings

In this section, we summarise the findings for both the country-and producer-level analyses. This synthesises the data from the individual studies to create estimates that are largely global, given the dominance of these four countries in global production. We present these according to the three cost categories, beginning with economic issues. We also include costs for the top ten producers, with a full write up for each country available in the appendices.

3.1 Economic issues

There are three economic variables that we consider:

- Opportunity costs of mortalities
- Cost of marine ingredients in feed
- Cost of lice fighting technologies

Opportunity costs of mortalities

Mortality rates on salmon farms are high and represent a substantial opportunity cost to salmon farmers.[21] Major contributing factors are lice, disease and their treatments, as well as algal blooms and warming seas. Salmon are also lost through escapes and many mortalities are unexplained.[22] Annual mortality statistics are only available for Norway and Scotland and both countries have seen increases in their rates since 2013, as the industry generates and runs up against increasing environmental pressures. These stem from lice/disease-induced mortalities and warming seas but also the fact that most of the available viable sites in both countries have already been exploited and there is a shortage of suitable coastline for open net cage farming.[23]

To estimate the opportunity cost for the two countries we have taken the annual salmon losses and multiplied them by the salmon price for each year. These results are displayed in Table 5. The combined cost since 2013 of these mortalities is USD$9.8 billion. If we apply the average mortalities for these two countries to Canada and Chile, we get an estimate of USD$768 million and $4.9 billion, respectively. Using this methodology, the total cost across the four countries is USD$15.5 billion.

Table 5: Mortality opportunity costs in Scotland, Norway, Canada and Chile

	2013	2014	2015	2016	2017	2018	2019	Total
International salmon price (USD per kg)	$6.72	$6.60	$5.31	$7.14	$7.44	$7.52	$6.92	
Norway								
Total harvest (mt)	1,168	1,258	1,303	2,133	1,236	1,282	1,357	
Mortalities (t)	127,347	145,969	177,255	309,375	180,508	164,096	196,809	
Percentage losses	11%	12%	14%	15%	15%	13%	15%	
Value of losses (MUSD)	855	983	940	2208	1343	1234	1409	**8908**
Scotland								
Total harvest (mt)	160	179	170	163	189	156	190	
Mortalities (t)	10,329	16,046	18,302	22,245	25,460	16,573	25,772	
Percentage losses	6.40%	9.00%	10.80%	13.60%	13.40%	10.60%	13.50%	
Value of losses (MUSD)	67	106	97	158	189	124	177	**922**
Canada								
Total harvest (mt)	97	86	121	123	120	123	120	
Value of losses (MUSD)	53	59	81	143	147	130	152	**768**
Chile								
Total harvest (mt)	636	803	735	643	778	809	907	
Value of losses (MUSD)	368	620	533	670	954	769	1022	**4939**

21 Soares, S., Green, D. M., Turnbull, J. F., Crumlish, M., & Murray, A. G. (2011). A baseline method for benchmarking mortality losses in Atlantic salmon (Salmo salar) production. Aquaculture, 314(1-4), 7-12.

22 Planet Tracker (2020) Dashboard: The Salmon Aquaculture Industry **https://planet-tracker.org/data-dashboards/oceans/salmon/**

23 Terazono, E. (2017) Norway turns to radical salmon farming methods *Financial Times* **https://www.ft.com/content/a801ef02-07ba-11e7-ac5a-903b21361b43**

Although the total figure relies on an estimate from Scotland and Norway, we know that salmon farms everywhere are experiencing similar environmental pressures because of poor fish husbandry, environmental practices and global warming. Indeed, in Chile, we would expect higher mortalities due to less stringent environmental regulations and a high incidence of lice infestation in recent years.[24] Even if we restrict the analysis to Norway and Scotland, the exercise reveals the scale of the economic cost this represents. The mortality rate of juveniles is expected to be even higher but there is poor reporting of mortality in hatcheries.[25] It is not possible therefore to include estimates of juvenile losses in this study and the figures presented here are therefore likely to underrepresent the scale and cost of salmon mortality.

Unfortunately, it is also expected that high mortalities will continue to be a problem for the industry. Whilst some mortalities are expected in any farming practice, salmon mortalities are high by the standards of other commonly farmed species. Studies of other aquaculture species have found survival rates of up to 99% once stocking densities are kept low.[26 27] In addition, mortality rates on egg laying hen farms are between 5 and 6%.[28] It is interesting to note that reducing mortalities to 5.5% on salmon farms in Norway would represent an annual saving of $892 million USD (based on 2019 volumes and prices).

Lice fighting technologies

Parasite and disease fighting technologies also represent a major cost to the industry. But they are also a function of poor fish husbandry, and therefore a potentially avoidable cost. There are also clear consumer concerns about the use of medicines and chemicals to control diseases and parasites.[29] When fish farms have high stocking densities – that is, fish are crowded together in a small environment with poor water flow - the spread of infectious diseases is hastened.[30] It also increases fish stress and makes them more susceptible to disease. Moreover, lice are more likely to spread rapidly in these conditions, and natural methods of removing lice, such as going upriver, are not available to the salmon.

In this section, we aggregate our estimates of the cost of using lice fighting technologies to slow the spread of parasites. Due to data limitations, we have not included the cost of disease control methods. However, as we will see addressing the lice threat represents a substantial cost on its own.

There are two means by which sea lice create costs for farmers. First, lice have been shown to reduce fish growth and appetite,[31] and second damage control measures can be costly, and some (such as delousing) can directly cause mortalities (as a result of stress from handling and secondary infections).[32] Cleaner fish are endorsed by some as a more natural alternative to medication but (leaving aside the impacts on their welfare) they are an ongoing cost as they are euthanised at the end of each growing cycle at which point a new crop are required. In addition, questions have been raised over their efficacy at reducing lice on a national scale.[33]

24 Mowi (2019) Annual Report **https://corpsite.azureedge.net/corpsite/wp-content/uploads/2020/03/Mowi_Annual_Report_2019.pdf**

25 Dyrevern (2019) New report reveals unnaturally high mortality in aquaculture hatcheries **https://dyrevern.no/dyrevern/new-report-reveals-unnaturally-high-mortality-in-aquaculture-hatcheries/**

26 Hayat, M. A., Nugroho, R. A., & Aryani, R. (2018). Influence of different stocking density on the growth, feed efficiency, and survival of Majalaya common carp (Cyprinus carpio Linnaeus 1758). F1000Research, 7.

27 Ronald, N., Gladys, B., & Gasper, E. (2014). The effects of stocking density on the growth and survival of Nile tilapia (Oreochromis niloticus) fry at son fish farm. Uganda. Journal of Aquaculture Research and Development, 5(2), 222.

28 Anon (n.d.) Understanding Mortality Rates of Laying Hens in Cage-Free Egg Production Systems **https://www.humanesociety.org/sites/default/files/docs/mortality-cage-free-egg-production-system.pdf**

29 Zander, K., & Feucht, Y. (2018). Consumers' willingness to pay for sustainable seafood made in Europe. Journal of international food & agribusiness marketing, 30(3), 251-275.

30 Nicholson, B. (2006) Fish Diseases in Aquaculture The Fish Site **https://thefishsite.com/articles/fish-diseases-in-aquaculture**

31 Abolofia, J., Asche, F., & Wilen, J. E. (2017). The cost of lice: quantifying the impacts of parasitic sea lice on farmed salmon. Marine Resource Economics, 32(3), 329-349.

32 **https://onlinelibrary.wiley.com/doi/10.1111/raq.12299**

33 **https://www.sciencedirect.com/science/article/abs/pii/S0020751920300126**

To ensure that we are not double counting the cost of mortalities, we have limited our analysis in this section to the cost of damage control measures, albeit these are only a portion of the costs. For Norway, cost estimates have already been generated by Nofima which estimates that the annual cost is in the region of USD$475 million.[34] This includes an estimated Kr1.5 billion on cleaner fish (based on a cost of Kr1.2 per Kg of salmon produced).[35]

For the other three countries, we drew on estimates developed by Costello.[36] This data (presented as cost per kg) was uprated from 2006 to today's prices. We also used the Nofima estimate to derive a cost per kg for Norway (which is similar to the estimates developed by Costello). We expect that these costs are conservative, as they have been estimated elsewhere for Norway at 9% of revenues.[37] These are multiplied by the kg produced each year to get an annual estimate. As we can see, from Table 6 the total for all four countries since 2013 is over USD$4 billion.

Table 6: Costs of lice control measures across four countries (MUSD)

Year	Cost per kg Canada	Cost per kg Scotland	Cost per kg Chile	Cost per kg Norway	Total cost Canada (MUSD)	Total cost Scotland (MUSD)	Total cost Chile (MUSD)	Total cost Norway (MUSD)	Total (MUSD)
2013	$0.112	$0.36	$0.28	$0.24	$12	$57	$176	$240	**$487**
2014	$0.114	$0.37	$0.29	$0.23	$11	$66	$232	$265	**$576**
2015	$0.116	$0.37	$0.30	$0.224	$16	$62	$222	$280	**$582**
2016	$0.117	$0.37	$0.31	$0.22	$17	$60	$199	$469	**$746**
2017	$0.119	$0.40	$0.32	$0.22	$17	$75	$247	$271	**$612**
2018	$0.122	$0.40	$0.33	$0.21	$17	$62	$263	$295	**$639**
2019	$0.125	$0.41	$0.34	$0.24	$17	$78	$304	$319	**$720**
Total (MUSD)					**$111**	**$463**	**$1,647**	**$2,142**	**$4,365**

Use of marine ingredients

Aquafeed is the largest single cost centre for salmon farmers, making up between 50 and 70% of costs.[38] Salmon farmers face rising costs of feed. This is perhaps greatest for fish meal (FM) and fish oil (FO), which are derived from wild fish. Due to the economic and environmental costs of using marine ingredients, their use has declined dramatically since 1990 when 90% of the feed was of marine origin.[39] The amount of FMFO still varies today across the countries from 10-14.5% in Norway to 12-18% for Canada and 15-25% in Scotland (based on latest available data).[40 41 42] A recent report for Chile reports that marine ingredients make up 7-9%.[43]

In later sections, we will explore the social and environmental implications of the use of FMFO in aquafeed. Here we consider the economic costs. To calculate these data, we drew on various sources of feed composition from the grey and academic literature. These are detailed for each country in the relevant appendix. The tonnage of FMFO was then

34 Nofima (2017) High lice costs, rising feed prices – and expensive land-based facilities **https://nofima.no/en/forskning/naringsnytte/high-lice-costs-rising-feed-prices-and-expensive-land-based-facilities/**

35 Nofima estimate of Kr1.2 per kg of salmon (based on 1.3 billion kg in 2018) **https://thefishsite.com/articles/counting-the-true-cost-of-combatting-sea-lice**

36 Costello, Mark. "The global economic cost of sea lice to the salmonid farming industry." Journal of fish diseases 32.1 (2009): 115.

37 Abolofia, J., Asche, F., & Wilen, J. E. (2017). The cost of lice: quantifying the impacts of parasitic sea lice on farmed salmon. Marine Resource Economics, 32(3), 329-349.

38 FAO (2018) The State of World Fisheries and Aquaculture 2018 **http://www.fao.org/documents/card/en/c/I9540EN/**

39 See Ytrestøyl, T., Aas, T. S., & Åsgård, T. (2015). Utilisation of feed resources in production of Atlantic salmon (Salmo salar) in Norway. Aquaculture, 448, 365-374.

40 Shepherd, C. J., Monroig, O., & Tocher, D. R. (2017). Future availability of raw materials for salmon feeds and supply chain implications: The case of Scottish farmed salmon. Aquaculture, 467, 49-62.

41 Aas, T.S, et al. 2019. Utilization of feed resources in the production of Atlantic salmon (*Salmo salar*) in Norway: An update for 2016. Aquaculture Reports 2019, vol 15.

42 Sarker, P. K., Bureau, D. P., Hua, K., Drew, M. D., Forster, I., Were, K., ... & Vandenberg, G. W. (2013). Sustainability issues related to feeding salmonids: a Canadian perspective. Reviews in Aquaculture, 5(4), 199-219.

43 Mowi (2019) Salmon farming handbook, 2019 **https://ml.globenewswire.com/Resource/Download/1766f220-c83b-499a-a46e-3941577e038b**

multiplied by the price of each commodity in the given year.[44] The results are displayed in Table 7. As we can see the cumulative costs are over USD$8 billion over the period.

Table 7 also shows that the costs of FMFO has remained relatively stable over the period. This is in spite of the fact that the Fish in/Fish out (FIFO) ratio has decreased (especially in Chile). As demand for salmon has continued to rise, the total amount of wild fish required has remained high. It demonstrates that unless marine ingredients are largely replaced as feed, the pressures on wild fish stocks will continue to increase in line with demand for salmon.

Table 7: FMFO costs in four countries (MUSD)

	2013	2014	2015	2016	2017	2018	2019	Total
Norway FM cost	$435	$428	$403	$346	$342	$350	$369	$2,676
Norway FO cost	$335	$335	$324	$288	$249	$352	$270	$2,156
Scotland FM cost	$64	$70	$66	$62	$71	$58	$70	$466
Scotland FO cost	$61	$63	$56	$51	$51	$57	$50	$393
Canada FM cost	$23	$30	$36	$35	$37	$41	$40	$246
Canada FO cost	$19	$26	$30	$29	$32	$35	$34	$208
Chile FM cost	$219	$190	$162	$136	$110	$109	$108	$1,037
Chile FO cost	$205	$176	$151	$130	$102	$139	$101	$1,007
Total cost	**$1,366**	**$1,321**	**$1,232**	**$1,081**	**$998**	**$1,144**	**$1,047**	**$8,192**

The reduction in the use of FMFO is driven partly by concern over impacts on wild fish stocks but also by increasing costs.[45] Most observers agree that as wild fish stocks come under increased pressure, and as the aquaculture industry expands, the costs of FMFO are set to rise. [46 47]A variety of alternate proteins have been identified to partially replace fishmeal and fish oil. These include insect feed, algae and bacterial protein. Analyses of the price differential between alternative and traditional feeds finds that the former are currently more expensive. [48] However, there are promising results from trials on the use of these feeds. One producer estimates that they could produce bacterial protein as an alternative feed for $1000 per tonne,[49] which is substantially less than the 2019 fish meal price of $1,418. In addition, significant investment is going into the alternative feed industries to scale production of these alternatives. The expectation is that over time they will be price competitive and eventually cheaper than FMFO. Insect meal has an added benefit of being generated by breaking down food waste into fats and proteins. It is estimated that food waste leads to £500 billion in lost value annually and Black Soldier Fly larvae can reduce food waste volume by up to 95% over a rapid two-week growing cycle.[50]

In the short term, the environmental benefits of using this highly promising insect meal in fish feed do not align with the economic interests of the aquaculture industry. However, in principle this positive externality could be incorporated into any social and environmental accounting of the aquaculture industry were these feeds to replace FMFO thereby (as will be discussed below) improving the social return from this industry.

44 Commodity prices were taken from the World Bank https://www.indexmundi.com/commodities/?commodity=fish-meal&months=120&currency=eur, EUFMA

45 Davidson, J., Barrows, F. T., Kenney, P. B., Good, C., Schroyer, K., & Summerfelt, S. T. (2016). Effects of feeding a fishmeal-free versus a fishmeal-based diet on post-smolt Atlantic salmon Salmo salar performance, water quality, and waste production in recirculation aquaculture systems. *Aquacultural Engineering*, *74*, 38-51.

46 Holland, J. (2017) Algae becoming increasingly relevant due to soaring fishmeal and fish oil demand, prices https://www.seafoodsource.com/news/supply-trade/algae-becoming-increasingly-relevant-due-to-soaring-fishmeal-and-fish-oil-demand-prices

47 FAO (2020) Early closure of the Peruvian fishing season pushes prices up http://www.fao.org/in-action/globefish/market-reports/resource-detail/en/c/1268631/

48 Arru, B., Furesi, R., Gasco, L., Madau, F. A., & Pulina, P. (2019). The introduction of insect meal into fish diet: the first economic analysis on European sea bass farming. Sustainability, 11(6), 1697.

49 Filou, E. (2020) Move over, fishmeal: Insects and bacteria emerge as alternative animal feeds https://news.mongabay.com/2020/04/move-over-fishmeal-insects-and-bacteria-emerge-as-alternative-animal-feeds/

50 Cordis (2017) Investigating the commercial feasibility of a novel biological enhancement technology for creating a sustainable, high value, insect-derived protein supplement for the EU aquaculture market https://cordis.europa.eu/project/id/775922/reporting/it

Costs for top ten producers

Table 8 lists the top ten salmon producers by revenues in 2018.[51]

Table 8: Top ten salmon producing companies by revenue (2018) (MUSD)

Company name	HQ	Total revenues in 2018 (MUSD)
Mowi	Norway	$4502
Leroy Seafood	Norway	$2783
Salmar	Norway	$1395
Grieg Seafood	Norway	$922
Norway Royal Salmon	Norway	$625
Bakkafrost	Faroe Islands	$504
Blumar	Chile	$503
Australis	Chile	$361
Camanchaca	Chile	$332
Invermar	Chile	$230

Source: Planet Tracker

The total revenues for these companies in 2018 were USD$12.157 billion dollars. In this section, we calculate the expected losses to these companies stemming from two highly material costs: mortalities and lice fighting technologies. As discussed elsewhere, lice outbreaks and mortalities from disease, escapes, predators and parasites are an indicator of both poor fish husbandry and sub-optimal fish welfare. These estimates will demonstrate that they also have a direct economic cost.

Using data from Planet Tracker's Salmon Dashboard Database, it is possible to calculate the number of mortalities and escapes by comparing the expected and actual harvest since 2010.[52] These data are drawn from the annual reports of the companies in question. Table 9 shows the results of these calculations. As we can see, there has been a difference of over half a million tonnes of salmon between actual and expected harvest over this period. This equates to almost USD$3.7 billion as set out in Table 2 (based on the average of the international salmon prices since 2010). Our estimate for the top four producing countries is USD$15.5 billion (see earlier discussion). Given that these countries make up 96% of global production, we might expect the cost to be closer to USD$7.75 billion. There are two potential explanations. First, there were gaps for several years in the dashboard, and due to the lack of transparency/agreed methodologies for reporting on mortalities, there may well be other inconsistencies. The second is that salmon farmers assume a minimum amount of mortalities per number of smolts released into pens, and most likely incorporate this into their harvest calculations. In this scenario, the difference between expected and actual harvests is therefore a measure of excess deaths, rather than total deaths. As a result of both of these scenarios, the volumes and costs reported here may well underestimate the total losses from mortalities.

51 Planet Tracker (2020) Loch-ed profits **https://planet-tracker.org/tracker-programmes/oceans/seafood/#loch-ed**

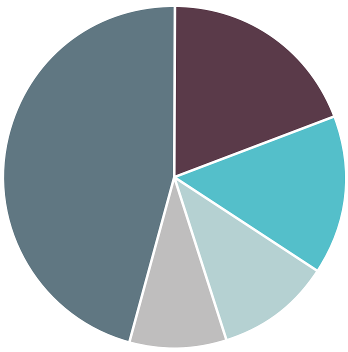
52 Planet Tracker (2020) Dashboard: The Salmon Aquaculture Industry **https://planet-tracker.org/data-dashboards/oceans/salmon/**

Table 9: Estimates of losses and associated costs (2010-2019)

Company	Volume of losses (tonnes)	Cost (MUSD)
Seafood Mowi	252,521	$1,719
Leroy Seafood	66,975	$456
Grieg Seafood	64,992	$442
Australis	34,042	$231
Blumar	32,236	$219
Norway Royal Salmon	28,342	$193
Bakkafrost	21,058	$143
Salmar	15,929	$108
Camanchaca	11,550	$78
Seafood Invermar	9,256	$63
Total	**536,901**	**$3,656**

These data also allow us to consider the main reasons for mortalities. These are displayed in Figure 1. As we can see, almost half are unexplained and in almost 20% no reason is given. Unexplained mortalities are those for which the cause of death has not been established, unlike those where no reason has been stated in the report. It is unclear as to why this proportion is so high given that research shows it should be possible to provide reasons in the vast majority of cases.[53] The other 30% of causes are split between algal blooms (9%), disease (11%), and sea lice (15%). In addition, over 2,000 tonnes of escapes were reported, which equates to 400,000 adult salmon (assuming they are harvested at about 5kg).[54]

Figure 1: Main causes of mortalities



The biggest known contributor to mortalities for these companies is therefore sea lice. Substantial amounts of money are spent to combat sea lice, including cleaner fish, delousing, and freshwater bathing. They are also a major contributor to mortalities (from the process of delousing as well as the parasites themselves), and a bottleneck to further expansion due to regulations designed to minimise lice infestations.[55]

In our country-level analyses, we used data from Costello (2009) (see above) to estimate the costs of treating sea lice. This study arrived at a global estimate of 6% of total revenues. Using this estimate, we can also estimate the costs of parasite control to the top salmon producers. Table 10 shows the revenues for each company since 2013, along with the parasite control estimates. Revenues have been adjusted for companies that produce commodities other than salmon (e.g., Blumar). All revenue data are extracted

53 Aunsmo, A., Bruheim, T., Sandberg, M., Skjerve, E., Romstad, S., & Larssen, R. B. (2008). Methods for investigating patterns of mortality and quantifying cause-specific mortality in sea-farmed Atlantic salmon Salmo salar. Diseases of aquatic organisms, 81(2), 99-107.

54 Anon (2017) Salmon Farming Industry Handbook **http://www.mowi.com/globalassets/investors/handbook/2018-salmon-industry-handbook.pdf**

55 Kragesteen, T. J., Simonsen, K., Visser, A. W., & Andersen, K. H. (2019). Optimal salmon lice treatment threshold and tragedy of the commons in salmon farm networks. *Aquaculture, 512*, 734329.

from the companies' annual reports and converted into dollars at current exchange rates.[56] As we can see, the total cost of combatting sea lice costs these companies almost USD$3.5 billion since 2013.[57]

Table 10: Estimates for cost of sea lice for top ten producers 2013-2019 (MUSD)

	Company	2013	2014	2015	2016	2017	2018	2019	Total
Australis	Revenues	$266	$272	$191	$347	$395	$360	$433	**$2,268**
	Cost of sea lice	$15	$16	$11	$20	$23	$21	$26	**$136**
Bakkafrost	Revenues	$391	$421	$447	$502	$591	$498	$708	**$3,561**
	Cost of sea lice	$23	$25	$35	$30	$26	$30	$35	**$206**
Camanchaca	Revenues	$251	$278	$262	$352	$334	$324	$272	**$2,077**
	Cost of sea lice	$15	$16	$15	$21	$20	$19	$16	**$124**
Norway Royal Salmon	Revenues	$275	$31	$339	$447	$522	$537	$591	**$2,746**
	Cost of sea lice	$16	$1.9	$20	$26	$31	$32	$35	**$164**
Grieg Seafood	Revenues	$254	$282	$487	$692	$742	$793	$878	**$4,132**
	Cost of sea lice	$15	$16	$29	$41	$44	$47	$52	**$247**
Salmar Leroy	Revenues	$1,139	$1,331	$1,423	$1,827	$1,971	$2,099	$2,162	**$11,955**
	Cost of sea lice	$68	$79	$85	$109	$118	$125	$129	**$717**
Mowi	Revenues	$2,972	$3,694	$3,766	$4,247	$4,415	$4,612	$5,004	**$28,711**
	Cost of sea lice	$178	$221	$225	$254	$264	$276	$300	**$1,210**
Invermar	Revenues	$99	$134	$67	$144	$219	$229	$173	**$1,069**
	Cost of sea lice	$5.9	$8	$4	$8.6	$13	$13	$10	**$64**
Blumar	Revenues	$217	$270	$195	$230	$197	$302	$234	**$1,647**
	Cost of sea lice	$13	$16	$11.7	$13.8	$11	$18	$14	**$98**

Together with the opportunity cost of mortalities set out above, we can see that the combined cost to top 10 producers is over USD$7.1 billion. This compares with total revenues of USD$58 billion since 2013, or 12% of total revenues over that period.

3.2 Environmental issues

Salmon farming is running up against several environmental pressures, which are inextricably linked to its commercial success, and these are a major source of risk for the industry. We have already seen how poor fish husbandry leads to increased outbreaks of disease, parasites and ultimately mortality. Poor environmental stewardship also contributes directly to mortalities. There are also indirect environmental risks. Atlantic salmon can only be farmed under certain conditions and as seas warm and available sites become exploited, the industry is running out of viable sites. This means that new sources of growth are dwindling. This creates pressure to locate farms in less suitable environments and to increase stocking densities, which further exacerbate environmental pressures. In addition, negative public perceptions of farmed salmon as an ethical product impact on consumer demand. This section will summarise these indirect costs and demonstrate how improved environmental outcomes could improve welfare and reduce costs. We consider four specific environmental impacts:

- Welfare loss of depleted salmon;
- Biodiversity loss of pelagic fish stocks;
- Impacts of local pollution; and
- Climate change impacts

56 These vary compared to revenues in Table 8 vary due to different exchange rates at the time of writing

57 In the previous section, we report that the lice control estimates for the four countries is $4bn. These were developed from lice treatment costs per kg. whereas this figure derives from a percentage of total revenue. As discussed earlier, the country-level analysis most likely underestimates the cost of lice.

Welfare loss of depleted salmon

Salmon farming impacts on fish stocks in three ways. Two of these have already been touched on: the use of pelagic fish in FMFO and the use of cleaner fish in parasite control. The third is the impact on wild salmon and trout stocks.[58] A recent study found that the presence of a salmon farm can lead to an average of 12-29% fewer adult wild salmon in the local area.[59] Salmon farms create risks to wild fish in several ways:

- Hybridisation - This is where escaped farmed salmon breed with the wild populations, reducing their ability to survive in the wild. Research suggests that these effects are likely to be passed on to future generations.[60]
- Inducing mortality by spreading lice and disease
- Local pollution

There has been serious concern about the status of wild Atlantic salmon stocks for many years now. The numbers of returning salmon have been plummeting[61] and reports from 2020 show that they are now at an historic low.[62] Whilst progress has been made in managing the interactions between farmed and wild salmon, serious risks remain and large-scale escapes are still regularly reported from salmon farms with Chile and Norway accounting for 60% of the largest escapes.[63] In this section, we seek to value the loss of wild salmon stocks and estimate the damage that is attributable to salmon farms.

In a review of the literature on the social, economic and cultural value of Atlantic salmon, Myrvold et al argue that this iconic fish provides humans with a range of values, benefits and gifts.[64] The review identified 41 studies of the different values of wild Atlantic salmon published between 2009 and 2019. Although these are dominated by economic studies, relative (for example) to studies of cultural value, it is nonetheless clear that the salmon has played - and continues to play - a role in the social, environmental and cultural life of communities along the Atlantic seaboard. The loss of habitat experienced by wild salmon - and driven in part by the expansion of aquaculture - is therefore something we would expect the public to be concerned about. This is confirmed by several contingent valuation studies on willingness to pay for salmon conservation. In a survey of the Canadian public, Pinfold[65] demonstrated over 80% support for investments in salmon restoration in the range of $4.50 to $12.50 per tax-paying household, translating into a total economic value of $57 million. In a US study of the non-market benefits of the Pacific Coho salmon, the authors[66] found that a programme aimed at increasing numbers of returning salmon can generate sizable benefits of up to $518 million per year for an extra 100,000 returning fish, even if the species is not officially declared recovered. It also found that the public attaches additional benefits to achieving conservation goals quickly. Studies such as these, have prompted NASCO[67] to claim that non-use values, such as existence and bequest values, may now substantially exceed values associated with recreational angling, which themselves exceed the commercial value of salmon as food.

58 It has been noted that mortality of sea trout is likely to be higher than in wild salmon, because they usually remain in coastal waters, where fish farms are situated (see Thorstad, E. B., & Finstad, B. (2018). Impacts of salmon lice emanating from salmon farms on wild Atlantic salmon and sea trout).

59 Thorstad, E. B., & Finstad, B. (2018). Impacts of salmon lice emanating from salmon farms on wild Atlantic salmon and sea trout.

60 Hindar, K., Fleming, I. A., McGinnity, P., & Diserud, O. (2006). Genetic and ecological effects of salmon farming on wild salmon: modelling from experimental results. ICES Journal of Marine Science, 63(7), 1234-1247.

61 Nasco (2020) State of North Atlantic Salmon **https://nasco.int/wp-content/uploads/2020/05/SoS-final-online.pdf**

62 Atlantic Salmon Federation (2020) 2020 State of Wild Atlantic Salmon Report **https://www.asf.ca/assets/files/asf-2020-state-of-population-v2.pdf**

63 Navarro, L. (2019) Here are the largest recorded farmed salmon escapes in history, Intrafish **https://www.intrafish.com/aquaculture/here-are-the-largest-recorded-farmed-atlantic-salmon-escapes-in-history/2-1-388082**

64 Myrvold, K. M., Mawle, G. W., Andersen, O., & Aas, Ø. (2019). The Social, Economic and Cultural values of wild Atlantic salmon. A review of the literature for the period 2009-2019 and an assessment of changes in values.

65 Pinfold, G. (2011). Economic Value of Wild Atlantic Salmon. Prepared by Gardner Pinfold. Accessed online: **https://www.asf.ca/assets/files/gardner-pinfold-value-wild-salmon.pdf**

66 Lewis, D. J., Dundas, S. J., Kling, D. M., Lew, D. K., & Hacker, S. D. (2019). The non-market benefits of early and partial gains in managing threatened salmon. PloS one, 14(8), e0220260.

67 Nasco (2020) The value of salmon. Accessed online: **http://www.nasco.int/value_changes.html**

Using these studies, it has been possible to place a value on the welfare costs to communities of the destruction of wild salmon stocks. The full methodology for each country is set out in the appendices. In summary, one study has found that lice from salmon farms kill 50,000 wild salmon in Norway per year.[68] If we assume that a similar number are killed due to infectious diseases, this gives us a total of 100,000 salmon at risk from salmon farms. We have excluded the impacts of escaped salmon, as the impacts are still not well understood. We also know that there are half a million fewer salmon returning to Norwegian rivers each year than there were in the 1980s.[69] Using these data we can estimate that 20% of the losses are as a result of salmon farming. This is also close to the midpoint of estimates for the Thorstad and Finstad study (2018). As we know the reductions in returning salmon in Scotland and Canada, we can apply these estimates to those countries also to work out the number of salmon potentially affected. Neither Atlantic, nor Coho salmon are native to Chile, and as a result we have not included Chile in this calculation. There are however significant concerns about the environmental impacts of farming non-native species in Patagonia, which is one of the world's most pristine ecosystems.[70]

To estimate the welfare loss, we have taken an average WTP of three studies from households in Canada, the UK and Ireland ($10, $20 and $18 respectively).[71] These represent the amount households would be willing to pay to restore salmon stocks. We then estimate a WTP to restore wild salmon stocks at the household level. A fifth of this cost gives us an annual cost to the three societies cumulatively (see Table 11).[72] The total welfare loss based on this calculation is USD$308 million. This is higher for Canada than Norway and Scotland due to the larger number of households included in the calculation.

Table 11: Estimate of welfare loss to households from destruction of wild salmon stocks attributable to aquaculture (2013-2019)

	2013	2014	2015	2016	2017	2018	2019
Norway	$7,228,141	$7,316,624	$7,413,270	$7,544,038	$7,674,806	$7,805,574	$7,805,574
Scotland	$9,601,368	$9,664,056	$9,719,772	$9,784,684	$9,850,944	$9,909,100	$9,982,492
Canada	$24,874,940	$24,874,940	$24,874,940	$28,144,160	$28,144,160	$28,144,160	$28,144,160

Biodiversity loss of pelagic and cleaner fish stocks

Pelagic fish are forage fish that are highly nutritious and are the main fish source used in the production of fishmeal and fish oil. Almost one-fifth of the world's annual marine wild-fish catch is taken out of the ocean for this purpose,[73] and in 2016, 69% of fishmeal and 75 percent of fish oil were used for seafood farming.[74] Of this, the vast majority is used in salmonid aquaculture.[75] However, forage fish also play a central role in the ecosystem as they are the primary food source for many marine mammals, seabirds, and larger fish,[76] with one study finding that three-quarters of ecosystems studied had

68 Castle, S. (2017) As Wild Salmon Decline, Norway Pressures Its Giant Fish Farms New York Times **https://www.nytimes.com/2017/11/06/world/europe/salmon-norway-fish-farms.html**

69 Norwegian Scientific Advisory Committee for Atlantic Salmon (29019) Status of wild Atlantic salmon in Norway 2019 Accessed online: **https://www.vitenskapsradet.no/Portals/vitenskapsradet/Pdf/Status%20of%20wild%20Atlantic%20salmon%20in%20Norway.pdf**

70 Bridson, P. (2014) Monteray Bay Aquarium Seafood Watch. Accessed online: **https://seafood.ocean.org/wp-content/uploads/2016/10/Salmon-Atlantic-Coho-Salmon-Chile.pdf**

71 Myrvold, K. M., Mawle, G. W., Andersen, O., & Aas, Ø. (2019). The Social, Economic and Cultural values of wild Atlantic salmon: A review of the literature for the period 2009-2019 and an assessment of changes in values. Lillehammer: Norwegian Institute for Nature Research.

72 Household data taken from **https://www.nrscotland.gov.uk/statistics-and-data/statistics/statistics-by-theme/households/household-estimates/2019**

73 Changing Markets Foundation (2019) Fish for Catastrophe **http://changingmarkets.org/wp-content/uploads/2019/10/CM-EX-SUMMARY-FINAL-WEB-FISHING-THE-CATASTROPHE-2019-.pdf**

74 FAO (2020) How fish is used. Accessed online: **http://www.fao.org/state-of-fisheries-aquaculture#:~:text=How%20is%20fish%20used%3F,food%20purposes%20(Figure%202)**

75 Sarker, P. K., Kapuscinski, A. R., Vandenberg, G. W., Proulx, E., Sitek, A. J., & Thomsen, L. (2020). Towards sustainable and ocean-friendly aquafeeds: Evaluating a fish-free feed for rainbow trout (Oncorhynchus mykiss) using three marine microalgae species. *Elementa: Science of the Anthropocene*, *8*.

76 Fréon, P., Cury, P., Shannon, L., & Roy, C. (2005). Sustainable exploitation of small pelagic fish stocks challenged by environmental and ecosystem changes: a review. Bulletin of marine science, 76(2), 385-462.

at least one highly and/or extremely dependent predator.[77] Although these fish may have historically been undervalued, this low commercial price has failed to take account of their wider economic and environmental value. Forage fish comprise 35-30% of global fish landings[78] (FAO, 2015; data from 2011 to 2013) with an annual catch value of $5.6 billion USD[79] (compared with the catch value of $87.7 billion USD for all marine fisheries.[80]

Forage fish provide a range of ecosystem services that are external to the market value of the fish, therefore. Measuring and valuing these benefits holistically is challenging given the interconnected and complex nature of the marine ecosystem. One proxy that we can consider is the estimate for the indirect value of forage fish (i.e., its contribution to the value of the commercial catch of predators which is estimated to be worth $11.3 billion). If we assume that this is based on global landings of about 51.5 million tonnes,[81] this gives us a figure of $219 per tonne. It is possible therefore to place a proxy value on the ecosystem loss of the total use of forage fish in each of the countries included in this analysis. These calculations are set out in Table 12. As we can see, the total indirect cost of the use of forage fish in salmon farming is almost USD$1.8 billion.

Table 12: Estimate of indirect cost of use of forage fish in salmon farming 2013-2019

	2013	2014	2015	2016	2017	2018	2019
Canada	$16,676,986	$14,749,795	$20,827,399	$21,100,028	$20,592,863	$21,042,291	$20,621,445
Scotland	$90,328,324	$100,740,000	$95,674,860	$91,735,307	$106,765,828	$87,809,824	$107,211,560
Norway	$97,333,014	$100,206,774	$98,997,243	$89,165,197	$89,362,881	$92,662,362	$98,105,070
Chile	€58,139,715	€52,357,001	€46,574,288	€40,791,574	€35,008,861	€35,008,861	€35,008,861

These figures only considered ex-vessel prices of predator fish dependent on forage fish. However, this is very likely an underestimate of the full economic benefits of predator fish (e.g., downstream benefits such as the supply chains of processors, distributors, and end consumers).[82] It also most likely underestimates wider ecosystem benefits to nonmarket predators, such as seabirds, seals and so on. As well as the existence value of these species discussed elsewhere, there can be additional economic benefits such as ecotourism revenue (whale watching, bird watching, etc.)[83] As pointed out by Koehn et al., focusing on the costs for fisheries, is only part of the cost benefit analysis.[84] Froehlich et al. assess whether FMFO use can circumvent forage fish limits (e.g. through greater consistent inclusion of fish byproducts). They find that this is possible by the middle of the 21st century. However, global shifts towards more pescatarian diets will make this impossible and increase the requirement for long-term, nutrient equivalent feed sources.[85]

The final wild fish impact is on cleaner fish. These are fish with a specialist feeding strategy, which involves removing lice from infested salmon. There are two main species used: lumpfish and wrasse. These fish had limited commercial value until their function as cleaner fish in captivity was discovered and their use has increased dramatically in the last decade as a result of salmon's evolving resistance to pharmaceutical

77 Pikitch, E., Boersma, P.D., Boyd, I.L., Conover, D.O., Cury, P., Essington, T., Heppell, S.S., Houde, E.D., Mangel, M., Pauly, D., Plagányi, É., Sainsbury, K., and Steneck, R.S. 2012. Little Fish, Big Impact: Managing a Crucial Link in Ocean Food Webs. Lenfest Ocean Program. Washington, DC. 108 pp.

78 FAO (Food and Agriculture Organization of the United Nations). (2015). The state of world fisheries and aquaculture. Opportunities and challenges.

79 Pikitch, E. K., Rountos, K. J., Essington, T. E., Santora, C., Pauly, D., Watson, R., ... & Cury, P. (2014). The global contribution of forage fish to marine fisheries and ecosystems. Fish and Fisheries, 15(1), 43-64.

80 Sumaila, U. R., Cheung, W., Dyck, A., Gueye, K., Huang, L., Lam, V., ... & Zeller, D. (2012). Benefits of rebuilding global marine fisheries outweigh costs. PloS one, 7(7), e40542.

81 Ibid.

82 Christensen, V., Steenbeek, J., & Failler, P. (2011). A combined ecosystem and value chain modelling approach for evaluating societal cost and benefit of fishing. Ecological Modelling, 222(3), 857–864.

83 Koehn, L. E., Essington, T. E., Marshall, K. N., Sydeman, W. J., Szoboszlai, A. I., & Thayer, J. A. (2017). Trade-offs between forage fish fisheries and their predators in the California Current. ICES Journal of Marine Science, 74(9), 2448-2458.

84 Ibid.

85 Froehlich, H. E., Jacobsen, N. S., Essington, T. E., Clavelle, T., & Halpern, B. S. (2018). Avoiding the ecological limits of forage fish for fed aquaculture. Nature Sustainability, 1(6), 298-303.

treatments.[86] In order to prevent disease transmission, cleaner fish are culled at the end of the production cycle, meaning that new fish are needed when the next production cycle begins.[87] The capture of wild fish has led to stock depletion[88] and farming of cleaner fish is now underway. However, as with salmon there is evidence of farmed cleaner fish escaping and hybridising with local populations.[89] Compared with salmon, there is limited research on cleaner fish; their biodiversity impacts and welfare are mentioned in passing but not widely studied. The main economic value of lumpfish has been for their roe but this is a niche and limited market. Several wrasse species are commonly used as display fish due to their vibrant colours. It is also interesting to note, as Erkinharju et al. point out,[90] that a species of wrasse has recently been reported as the first fish to seemingly pass the mirror mark test, a behavioural technique used to measure and determine whether an animal possesses self-awareness. Although the study has received criticism, such findings may have implications for fish welfare and subsequently the use of cleaner fish in aquaculture. Despite this, due to the uncertainty around potential impacts, it has not been possible to quantify any cleaner fish costs in this study. However, more research is required on the implications of use of both wild and farmed cleaner fish, especially in light of survey findings showing that fish farmers question whether cleaner fish are an effective delousing method that actually results in fewer delousing operations.[91]

Impacts of local pollution

Aquaculture activities are an interconnected part of the ecosystem in which they exist, and salmon farms make use of 'free' coastal ecosystem services such as fresh, clean water, appropriate temperatures, nutrient levels and so on.[92] They also contribute to their deterioration, however, as a result of local pollution impacts. Pollutants from salmon aquaculture consist of uneaten feed and faeces, which are directly discharged into the marine environment. These result in eutrophication from the accumulation of nutrients like phosphorous and nitrogen, or what are known as algal blooms. These can lead to large mortality events, and the economic costs of these has been at least partly included above.

For the environmental impacts, there are two available methods to estimate their costs: the pollution abatement cost (PAC) consumer WTP for higher environmental standards. Data exist on the former for Norway and the latter for Canada and Scotland. However, to increase consistency between the countries, we have used the PAC and applied the Norwegian figure to the other three countries.

The pollution abatement cost (PAC) measures the amount that would be required to preserve or restore a unit of the environmental good in question. [93] Unless the full PAC is accounted for, salmon farms are 'free riding' on free environmental services. Liu et al. have found the PAC for Norway to be 3.5% of total salmon production.[94] Although a little out of date, we know that algal blooms are a continuing - and perhaps worsening - problem for Norwegian aquaculture (in 2019, 8 million salmon were killed in an algal

86 Faust, E., Halvorsen, K. T., Andersen, P., Knutsen, H., & André, C. (2018). Cleaner fish escape salmon farms and hybridize with local wrasse populations. Royal Society Open Science, 5(3), 171752.

87 Erkinharju, T., Dalmo, R. A., Hansen, M., & Seternes, T. (2020). Cleaner fish in aquaculture: review on diseases and vaccination. Reviews in Aquaculture.

88 Kennedy, J., Durif, C. M., Florin, A. B., Fréchet, A., Gauthier, J., Hüssy, K., ... & Hedeholm, R. B. (2019). A brief history of lumpfishing, assessment, and management across the North Atlantic. ICES Journal of Marine Science, 76(1), 181-191.

89 Faust, E., Halvorsen, K. T., Andersen, P., Knutsen, H., & André, C. (2018). Cleaner fish escape salmon farms and hybridize with local wrasse populations. Royal Society Open Science, 5(3), 171752.

90 Erkinharju, T., Dalmo, R. A., Hansen, M., & Seternes, T. (2020). Cleaner fish in aquaculture: review on diseases and vaccination. Reviews in Aquaculture.

91 The Norwegian Institute of Marine Research is also concerned about the method's lack of documented effectiveness. **https://norwegianscitechnews.com/2020/04/cleaner-fish-being-sacrificed-in-the-fight-against-salmon-lice/**

92 Custódio, M., Villasante, S., Calado, R., & Lillebø, A. I. (2020). Valuation of Ecosystem Services to promote sustainable aquaculture practices. Reviews in Aquaculture, 12(1), 392-405.

93 Nikitina, E. (2019). Opportunity cost of environmental conservation in the presence of externalities: Application to the farmed and wild salmon trade-off in Norway. Environmental and resource economics, 73(2), 679-696.

94 Liu, Y., & Sumaila, U. R. (2010). Estimating pollution abatement costs of salmon aquaculture: a joint production approach. Land Economics, 86(3), 569-584.

bloom in just a few days).[95] Due to the lack of comparable data for the other countries, we have also applied this estimate. As with Norway, the evidence would suggest that algal blooms continue to be a problem for the other three countries. In addition, environmental standards are at least as high (and in many cases higher) in Norway than the other countries. Separate calculations on WTP for higher environmental standards have been calculated for Scotland and Canada and are provided in the appendices. Table 13 provides details of the PACs for each country.

Table 13: Pollution Abatement Costs for four countries (MUSD)

	2013	2014	2015	2016	2017	2018	2019	Total
Norway	$274	$290	$242	$533	$322	$337	$328	$2328
Scotland	$37	$41	$31	$40	$49	$41	$46	$288
Canada	$22	$19	$22	$30	$31	$32	$29	$189
Chile	$149	$185	$136	$160	$202	$213	$219	$1268

As we can see from Table 13, the estimate for cumulative local pollution costs across the four countries is over USD$4 billion.

Climate change impacts

Although aquaculture is often positioned as a sustainable alternative to other forms of farming, there are substantial CO^2 emissions from air freight and aquafeed, which are not usually accounted for in environmental reports. Whilst the farmgate emissions from aquaculture are low relative to agriculture, it is argued that these estimates underestimate the true carbon cost.[96] Life cycle analysis provides a more complete estimate of carbon emissions because it includes impacts throughout the supply chain. Life cycle analysis of carbon emissions across producer countries shows that Norway has the lowest impacts per unit production, whereas impacts are consistently highest in the UK due to the embedded carbon in the feedstuffs used.[97] Several studies also show that feed provision is the single most important contributor to resource use and emissions.[98]

Sintef have estimated the full CO2 emissions for Norway including previously uncounted impacts. These include the impacts of the use of soy in fish feed and its impact on deforestation in Brazil (all of Norway's soy is sourced in Brazil). It also takes account of air freight in the distribution of salmon, which is increasing due to the increased importance of China as a consumer of Norwegian salmon. The total carbon emissions produced by the sector are 9.685 million tonnes (or about 8 kg of carbon per kg of salmon). There are various methods for costing carbon emissions, and a wide literature on the appropriate valuations to use. If we conservatively use the carbon tax applied by Norway to fishing to this figure ($27 USD per tonne) we get an annual value of $255 million per year.[99] However, this value is substantially higher when a social cost of carbon is applied. Table 14 shows the emissions costs associated with each of the four countries based on the Norwegian LCA data and using the UK's Department for Climate Change estimate of USD$72 per tonne.[100] This gives a total cumulative emissions cost of USD$8.3 billion. An important caveat here is that these estimates are certainly lower than emissions from alternative protein sources such as land-based animals. However, the purpose of the

95 Magra, I. (2019) Millions of Salmon in Norway Killed by Algae Bloom. *New York Times* Accessed online: **https://www.nytimes.com/2019/05/23/world/europe/salmon-norway-algae-bloom.html**

96 Newton, R. W., & Little, D. C. (2018). Mapping the impacts of farmed Scottish salmon from a life cycle perspective. The International Journal of Life Cycle Assessment, 23(5), 1018-1029.

97 Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., ... & Silverman, H. (2009). Not all salmon are created equal: life cycle assessment (LCA) of global salmon farming systems.

98 Ibid.

99 Bruvoll A. and Dalen H. (2009) Pricing of CO2 emissions in Norway. Accessed online: **https://www.ssb.no/a/english/publikasjoner/pdf/doc_200916_en/doc_200916_en.pdf**

100 Defra (2006) The social cost of carbon (SCC) review **https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/243816/aeat-scc-report.pdf**

section is to highlight that emissions from this industry are higher than the industry tends to claim.

Table 14: Cumulative costs of CO^2 emissions in salmon farming (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Norway	$626	$674	$699	$1,144	$663	$687	$728
Scotland	$86	$96	$91	$87	$101	$83	$102
Canada	$52	$46	$65	$66	$64	$66	$64
Chile	$264	$345	$326	$285	$329	$354	$376

3.3 Social issues

In this section, we consider two of the main social concerns relating to salmon farming

- Salmon welfare and
- Impacts of diverting pelagic fish away from direct human consumption for use in FMFO

Salmon welfare

Salmon welfare is a result, among other things, of the fish's health, environment, farming methods and routines, and is a direct function of factors such as stocking density, prevalence of parasites and disease, and water quality.[101] Given that these factors also determine profitability, fish welfare is arguably negatively correlated with profitability in the short-term. However, there is also a long run economic argument to be made. There is plenty of evidence that poor fish husbandry increases mortality and the need for costly disease and lice fighting technologies.[102] Moreover, there are strong, and growing consumer preferences for ethically produced seafood, especially in Europe.[103] In Norway, for example, surveys have found that animal welfare is more important to consumers than other ethical consideration such as organic, local production and environmental standards.[104] Although it may not be as high on the agenda as land-based animal welfare, a Eurobarometer survey from 2016[105] found that two-thirds of adults across nine European markets agree that fish are sentient and that fish feel negative emotions. In addition, animal husbandry issues are gaining weight in consumers' food choices, including preferences for higher fish welfare,[106] although this tends to be higher for consumers who understand sustainability issues, consume seafood regularly and have higher incomes.

These consumer preferences can be incorporated into an economic analysis using contingent valuation studies. The calculation applied to Norway, Scotland and Canada was based on an estimate that the average European consumer was willing to pay a price premium of 14% for salmon with higher welfare standards. [107] In Table 4, we apply this to European/Norwegian/UK consumers of Norwegian and Scottish salmon, and to domestic consumers of Canadian salmon (15%). This is plausible as there is plenty of

101 Stien, L. H., Tørud, B., Gismervik, K., Lien, M. E., Medaas, C., Osmundsen, T., ... & Størkersen, K. V. (2020). Governing the welfare of Norwegian farmed salmon: Three conflict cases. Marine Policy, 117, 103969.

102 Norwegian Veterinary Institute (2018) Fish Health Report 2018 **https://www.vetinst.no/rapporter-og-publikasjoner/rapporter/2019/fish-health-report-2018**

103 Zander, K., & Feucht, Y. (2018). Consumers' willingness to pay for sustainable seafood made in Europe. Journal of international food & agribusiness marketing, 30(3), 251-275.

104 Salmon Group (2020) Fish welfare in fish farming **https://salmongroup.no/wp-content/uploads/2020/09/SG_Fiskevelferd_ENG_Digital.pdf**

105 Savanta ComRes Eurogroup for Animals: CIWF Fish Welfare Survey. Accessed online: https://comresglobal.com/polls/eurogroup-for-animals-ciwf-fish-welfare-survey

106 Inter alia: Kalshoven, K., & Meijboom, F. L. (2013). Sustainability at the crossroads of fish consumption and production ethical dilemmas of fish buyers at retail organizations in The Netherlands. Journal of agricultural and environmental ethics, 26(1), 101-117. Kupsala, S., Jokinen, P., & Vinnari, M. (2013). Who cares about farmed fish? Citizen perceptions of the welfare and the mental abilities of fish. Journal of Agricultural and Environmental Ethics, 26(1), 119-135.; Pieniak, Z., Vanhonacker, F., & Verbeke, W. (2013). Consumer knowledge and use of information about fish and aquaculture. Food policy, 40, 25-30.

107 Zander, K., & Feucht, Y. (2018). Consumers' willingness to pay for sustainable seafood made in Europe. Journal of international food & agribusiness marketing, 30(3), 251-275.

evidence that Canadians care about animal welfare and animal welfare standards are somewhat similar in Canada and the EU. We have excluded salmon consumed outside of the EU/Norway/UK/Canada. These results are displayed in Table 15. The total cost across the four countries from poor fish welfare is USD$4.67 billion.

Table 15: Salmon welfare premium (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Norway	$271	$374	$434	$629	$603	$649	$713
Scotland	$117	$130	$107	$114	$149	$136	$145
Canada	$9	$9	$10	$16	$16,	$17	$17

This proxy value demonstrates that fish welfare is material to consumers. Although the valuation approach could potentially be criticised as being anthropomorphic, valuation is intrinsically a human endeavour meaning that value can only be ascribed to humans, hence the emphasis on human perception of welfare in this instance.

There are also concerns over the welfare of wild wrasse on fish farms. Wrasse require shelters for protection when at rest and from tides and currents, supplementary feeding when lice numbers are low, and care during farm operations such as grading, and moving salmon, and net cleaning.[108] However, mortality rates are very high. For example, 23 million wild wrasse were caught in Norway in 2018 and 40% of these died in the same year. Due to a lack of data on welfare impacts, it was not possible to include a valuation of cleaner fish welfare in the model.

Impacts of diverting pelagic fish away from direct human consumption (DHC)

This section considers the impacts of diverting forage fish away from DHC in low and middle-income countries for use in the FMFO industry, in large part to feed European aquaculture. In this context, the two most important regions for pelagic fish are West Africa and the Pacific coast of South America, most notably Peru.

Peru is the top exporter of fishmeal and fish oil worldwide and landings of anchoveta are used nearly exclusively for FMFO production, despite a proactive national food policy aimed at favouring their direct human consumption in an effort to tackle Peru's substantial undernutrition problem.[109] There has also been a long-term decline in anchoveta stocks.[110] As with sardine, these support a wide variety of species. This includes other fish that are then used for DHC. Research quoted by the Changing Markets Foundation shows that the decline of fish stocks now leads to Peruvians eating more frozen imported fish.[111] Unfortunately, there are limited data quantitative data available on Peru to incorporate into this analysis.[112]

108 Treasurer, J., & Feledi, T. (2014). The Physical Condition and Welfare of Five Species of Wild-caught Wrasse Stocked under Aquaculture Conditions and when Stocked in Atlantic Salmon, Salmo salar, Production Cages. Journal of the World Aquaculture Society, 45(2), 213-219.

109 Fréon, P., Sueiro, J. C., Iriarte, F., Evar, O. F. M., Landa, Y., Mittaine, J. F., & Bouchon, M. (2014). Harvesting for food versus feed: a review of Peruvian fisheries in a global context. Reviews in Fish Biology and Fisheries, 24(1), 381-398

110 Tegel, S. (2013) Peru: Where have all the anchovies gone? Accessed online: **https://www.pri.org/stories/2013-04-14/peru-where-have-all-anchovies-gone**

111 Changing Markets Foundation (2019) Until the Seas run Dry **http://changingmarkets.org/wp-content/uploads/2019/04/REPORT-WEB-UNTILL-THE-SEAS-DRY.pdf**

112 For more information on anchoveta and FMFO in Peru see Changing Market's Foundation *What Lies Beneath report* **http://changingmarkets.org/wp-content/uploads/2020/11/What_Lies_Beneath_full_report.pdf**

Another growing exporter of FMFO are the countries along the West African coast: Senegal, Mauritania and the Gambia. 15 percent of Africa's catches are reported as destined for non-food uses, such as FMFO and most of this comes from West Africa,[113] where it has been identified as a future growth area. The biodiversity losses from use of fish in aquafeed have been discussed above. Here we consider the socio-economic cost for local fishing communities. The main pelagic species fished in West Africa is sardinella, and Cashion et al argue that 90% of this food is food-grade or prime food-grade fish.[114] This is important in three ways. First, West African countries have significant food security issues (almost 30% of under-5s experience stunting as a result of under-nutrition).[115] Fish are an important provider of nutrients and animal protein and it is argued that current and potentially increasing use for non-DHC may represent a challenge to global food security.[116]

Second, the growth of the FMFO industry may lead to net economic losses. The companies are largely foreign-owned and funded by foreign investment.[117] Production has a shorter local supply chain than the direct selling of fish locally/regionally, and other forms of processing, such as canning or freezing. [118] This means that a smaller proportion of the value added from the fish is being captured by local people. This decreases the stocks available for local fishermen and the subsequent jobs that are created from the building of boats, through to the preparing of meals using the fish, such as smoking at local markets. Many of these roles employ women who may have few employment opportunities. In a review of the contribution of fisheries to livelihoods and nutrition, Bené et al. conclude that the evidence convincingly shows that women's roles in capture fisheries and their contribution either go unrecorded or are undervalued and remain largely invisible in national statistics.

Finally, demand for small pelagics increases the pressure on fish stocks in the region. These areas are already heavily overfished, largely through the access that European and Chinese trawlers have to the waters.[119] The current rates of extraction are found to be driving several species towards extinction.[120] This is further placing the livelihoods of those that depend on fishing at risk leading to increasing poverty and forced migration.[121] [122] The most threatened species include forage fish such as sardinella and the UN estimates that declining availability could seriously undermine food security across the region.[123]

113 Wijkström, U. N. (2009). The use of wild fish as aquaculture feed and its effects on income and food for the poor and the undernourished. In Fish as feed inputs for aquaculture: practices, sustainability and implications (Vol. 518, pp. 371-407). FAO Rome.

114 Cashion, T., Le Manach, F., Zeller, D., & Pauly, D. (2017). Most fish destined for fishmeal production are food-grade fish. Fish and Fisheries, 18(5), 837-844.

115 Global Nutritional Report (2020) Western Africa Nutrition Profile **https://globalnutritionreport.org/resources/ nutrition-profiles/africa/western-africa/#:~:text=The%20Western%20Africa%20subregion%20experiences,the%20global%20average%20of%2021.9%25.**

116 Béné, C., Arthur, R., Norbury, H., Allison, E. H., Beveridge, M., Bush, S., ... & Thilsted, S. H. (2016). Contribution of fisheries and aquaculture to food security and poverty reduction: assessing the current evidence. *World Development*, *79*, 177-196.

117 Greenpeace. (2019) A Waste of Fish **https://www.greenpeace.org/international/publication/22489/waste-of-fish-report-west-africa/**

118 Wijkström, U. N. (2009). The use of wild fish as aquaculture feed and its effects on income and food for the poor and the undernourished. In Fish as feed inputs for aquaculture: practices, sustainability and implications (Vol. 518, pp. 371-407). FAO Rome

119 Munshi, N. (2020) The Fight for West Africa's Fish **https://www.ft.com/content/0eb523ca-5d41-11ea-8033-fa40a0d65a98**

120 **https://www.odi.org/sites/odi.org.uk/files/resource-documents/10665.pdf**

121 Jönsson, J. H., & Kamali, M. (2012). Fishing for development: A question for social work. International Social Work, 55(4), 504-521

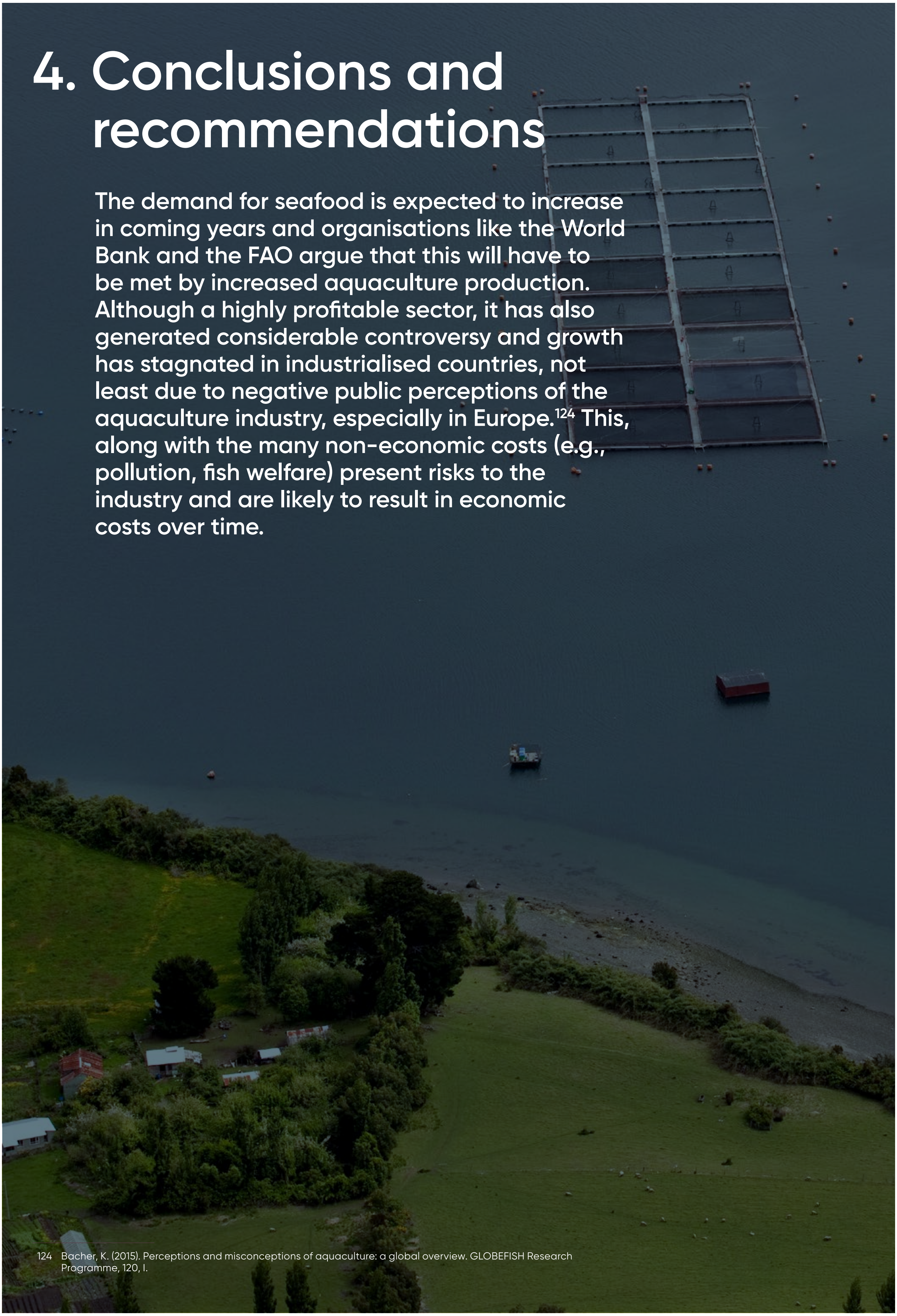
122 Alder, J., & Sumaila, U. R. (2004). Western Africa: a fish basket of Europe past and present. The Journal of Environment & Development, 13(2), 156-178.

123 **https://www.iucn.org/news/secretariat/201701/overfishing-threatens-food-security-africa%E2%80%99s-western-and-central-coast-many-fish-species-region-face-extinction-%E2%80%93-iucn-report**

The main country in our study to import FMFO from West Africa is Norway, which is the second largest importer of FMFO from Mauritania. Most marine ingredients used in Canada, Chile and Scotland come from Peru. Due to limited quantitative evidence on the impacts in relation to Peru, we have excluded these from the analysis. Estimates have been produced for Norway and are described in Box 1.

Box 1: Estimate of cost to Mauritania of exported FMFO to Norway

In 2019, Norway imported almost 8.5 thousand tonnes of fish oil from Mauritania, for use in the salmon farming industry. Data are not currently available for Mauritania, but an estimate by Wijkström for Asia suggests that if bycatch were not being used for fish farming in Asia, it would hypothetically create between 8.1 and 10.2 million jobs in post-harvest activities and processing. This equates to a minimum of 5 jobs per tonne of fish or 44,255 jobs lost in the supply chain for the amount of fish oil sold to Norway. If we multiply this by the GDP per head for Mauritania ($1188), it gives us a total value of $55.5 million. Even when we subtract the value of the fish oil exports ($16.8 million), we are left with a loss of $37.5 million in 2019. There was insufficient data to carry out a retrospective analysis



4. Conclusions and recommendations

The demand for seafood is expected to increase in coming years and organisations like the World Bank and the FAO argue that this will have to be met by increased aquaculture production. Although a highly profitable sector, it has also generated considerable controversy and growth has stagnated in industrialised countries, not least due to negative public perceptions of the aquaculture industry, especially in Europe.[124] This, along with the many non-economic costs (e.g., pollution, fish welfare) present risks to the industry and are likely to result in economic costs over time.

124 Bacher, K. (2015). Perceptions and misconceptions of aquaculture: a global overview. GLOBEFISH Research Programme, 120, I.

4.1 Conclusions

In this paper, we have sought to fill gaps in understandings of the economic, social, and environmental costs of salmon farming in the top producing countries. The estimates presented in this analysis are summarised in Table 16. We have used a conservative approach throughout, and although we encountered significant data gaps, we have been able to provide values for most of the variables. The analysis suggests that salmon aquaculture has produced private and external costs of almost USD$50 billion over the 7-year period being studied.

Table 16: Summary of costs (in MUSD)

Variable	Canada	Norway	Chile	Scotland	Total
Mortalities	768	8908	4939	922	15,539
Lice	111	2142	1647	463	4,365
FMFO	454	4832	2045	859	8,192
Total economic cost	**1333**	**15969**	**8631**	**2233**	**28,096**
Salmon stocks	*187*	*52*	Insufficient data	*68*	308
Pelagic fish stocks	*135*	*665*	302	*680*	1,784
Local pollution	*189*	*2328*	1268	*288*	4,073
Climate change	*425*	*5224*	2282	*425*	8,356
Total environmental cost	**936**	**8269**	**3852**	**1461**	**14,521**
Fish welfare	*97*	*3675*	Insufficient data	902	4,674
Total social cost	**97**	**3675**	Insufficient data	**902**	**4,674**
Total	**3587**	**27913**	**13304**	**4596**	**47,291**

This report has focused on the negative externalities from salmon farming. On the benefit side, we might want to consider factors such as consumer and producer surplus of increased aquaculture as well as employment in coastal communities where there may be limited industry. Table 17 lists some of the economic benefits that have been found elsewhere.

Table 17: Examples of positive benefits from salmon farming

Location	Benefit
Norway	Fisheries value chain is estimated to contribute USD$11 billion to GDP per annum[125]
British Colombia	Salmon farming supports 7,000 jobs in coastal communities and contributes about $1.5 billion to the provincial economy annually.
Chile	Estimated to have created a total of 60,000 jobs since it began to grow in the 1990s[126]
Scotland	Estimated to have contributed $2 billion to the Scottish economy annually

However, it is not uncommon for economic studies to be commissioned by the industry itself, or governments keen to support expansion (see Box 2 for a discussion of the use of cost benefit analysis in Scotland). Whilst this study has excluded positive impacts, it has also been unable to assess some negative impacts such as the effects on coastal tourism. For example, a study in Norway that compares consumer/producer surplus to

125 Johansen, U., Bull-Berg, H., Vik, L. H., Stokka, A. M., Richardsen, R., & Winther, U. (2019). The Norwegian seafood industry–Importance for the national economy. Marine Policy, 110, 103561.

126 Naru, A., & Shoaib, F. (2019). International Trade of Chilean and Tasmanian Salmon and the Governmental Human Resource Policy enabling its Expansion. Latin American Journal of Trade Policy, 2(3), 5-14.

opportunity costs for land/sea use finds that parts of the producer surplus have to be reinvested in the regional economy to create a positive return for a region.[127]

Considering the full range of costs and benefits may well demonstrate positive benefits from aquaculture (and even salmon farming). Yet what this report shows is that there are substantial costs that are not included on the balance sheet and that the scope for improved environmental and social performance is considerable. In addition, a combination of growing environmental risks, consumer demand for ethical products and limits to poor fish husbandry are creating long run economic risks to the industry, that can only be mitigated by investing in more sustainable farming practices.

Box 2: Cost benefit analysis and Scottish salmon farming

There have been several recent attempts to demonstrate the positive contribution of salmon farming to the Scottish economy and local rural communities.[128] These have been commissioned by both the Scottish Government and the Scottish salmon industry. For example, the Scottish Salmon Producer's Organisation has calculated that the industry is worth over £2 billion to the economy annually. Reports by Imani and Westbrook (2017) and Marsh (2019) also found net positive benefits. The latter reports have been critiqued by Riddington et al.[129] for Salmon and Trout Conservation Scotland who found that estimates for Gross Value Added (GVA) and employment were overestimated by 124% and 251% respectively. The report concluded the evidence did not support industry expansion when the impacts to the whole of society are considered. This report was peer reviewed by Bridge Economics[130] who firmly endorsed the critiques and concluded that addressing quantitative oversights to bring the analysis in line with the Treasury's guidance on cost benefit analysis would have led to a less charitable assessment of the underlying economic arguments. These critiques are not arguing that salmon farming is net negative to Scotland, rather that the economic analyses contain positive biases and are partial because they do not consider costs and benefits to a wide enough range of stakeholders and exclude non-economic impacts.

4.2 Recommendations

Our recommendations focus on the four most significant stakeholders in salmon farming: governments, investors, farmers and consumers. The industry requires increased investment in technologies to address environmental, economic and social risks described in this report. Each of these groups has the potential to benefit and/or bear costs from salmon farming, and each should, as a result, be prepared to contribute proportionately towards the transformation that is required. Bespoke recommendations for each group are therefore provided.

127 Aanesen, M., & Mikkelsen, E. (2020). Cost-benefit analysis of aquaculture expansion in Arctic Norway. Aquaculture Economics & Management, 24(1), 20-42.

128 SSPO (2020) Estimation of the Wider Economic Impacts of the Aquaculture Sector in Scotland **https://www.scottishsalmon.co.uk/reports/wider-economic-impacts-of-the-scottish-aquaculture-sector**; Imani Developments and Steve Westbrook, **http://imanidevelopment.com/wpcontent/uploads/2017/08/Value-of-Scottish-Aquaculture-2017-Report.pdf** Richard Marsh/Four Consulting (2019), Key Figures for Scottish Salmon, **https://d178ivhysawugh.cloudfront.net/1556530716/salmon-impact.pdf**

129 Riddington, G. Radford, A. and Gibson, H. (2020) The Economic Contribution of Open Cage Salmon Aquaculture to Scotland: A Review of the Available Economic Evidence **https://www.salmon-trout.org/wp-content/uploads/2020/04/Riddington-Radford-Gibson-Economic-Contribution-of-Salmon-Aquaculture-to-Scotland.pdf**

130 Bridge Economics (2020) Peer Review of the Economic Contribution of Salmon Aquaculture to Scotland **https://www.salmon-trout.org/wp-content/uploads/2020/04/Peer-Review-of-the-Economic-Contribution-of-Salmon-Aquaculture-to-Scotland-exec-summary.pdf**

For governments

Economic benefits of salmon farming need to be balanced against other coastal industries such as tourism, angling and wider environmental impacts. Better oversight and more robust regulation of salmon farming should lead over time to competitive advantage as consumers increasingly seek out more ethical and environmentally friendly products. Governments can lead the way on this by restricting licences to companies that meet higher social and environmental standards.

The industry would benefit from guidelines for sustainable feed ingredients along with stricter due diligence and governance frameworks in aquafeed supply chains. Governments should also support the phase-out of whole wild-caught fish for use in aquafeed. Furthermore, aquaculture that relies on wild-caught fish should not receive any subsidies or other public support measures.

Policy should support the development of alternative technologies (for feedstuffs and better farming methods) and provide economic incentives for a transition to more sustainable ingredients and farming practices.

Governments should require more transparent reporting in this industry, as is required in agriculture, and should resist industry pressure not to publish mortalities data that are in the public interest. Countries such as Canada that do not publish these data may be placing themselves at a disadvantage if mortalities data are more positive than those reported here. In addition, consumers increasingly expect transparency in supply chains and companies/sectors which fail to respond to that expectation will place themselves at a disadvantage in the market.

More generally there is a need to improve the quality of social, economic, and environmental accounting in salmon farming. This would have the dual benefit of supporting more holistic decision-making and incentivising better farming practices. By revealing costs and benefits, governments could create a race to the top amongst salmon farmers, and a level playing field for small producers that may be operating to higher standards. At a minimum, governments (e.g., in Scotland) should refrain from using economic analysis to make a priori economic arguments in favour of salmon farming, given their responsibilities to a wider group of stakeholders.

For investors

As a result of growing environmental and regulatory pressures, investment decisions are required that drive a rapid transition towards alternative feeds and farming practices. These technologies already exist but require more investment to make them viable in the short-term.

Although the risks of existing farming practices are often understood, investors continue to support them perhaps to the continued short-run profitability of the sector. This creates a barrier to the adoption of new technologies and improved practices, and investors need to take a long-term view. This may involve accepting lower returns in the short term but as discussed in this paper issues with both supply and demand should create competitive advantage in the long run.

For farmers

Mortalities, lice treatments and disease are creating huge costs for the farmers and damaging the reputation of farmed salmon. Significant opportunities exist to dramatically improve the environmental and social performance of salmon production through a focus on the development of least-environmental cost (as opposed to least-economic-cost) feed formulations. These technologies exist and have been shown to work and producers should in particular work with the aquafeed industry to remove wild caught fish entirely from the formulations. This would also appeal to the growing consumer demand for an ethical product. In addition, the cost of marine ingredients is expected to increase, these may also prove to be a lower cost alternative in the medium term.

As demonstrated in this report, poor fish husbandry is a false economy as it leads to significant direct and indirect costs. We recommend therefore that farmers adopt better practices, such as stocking densities commensurate with higher survival rates. Finally, the industry should also prioritise cultivating non-carnivorous species or those that require less or no feed.

For consumers

Salmon was once a high value food that was only available in season and consumed on special occasions. In line with the need for investment from all stakeholders, some consumers should also be prepared to pay more for salmon where their economic circumstances allow, and/or to consume it more infrequently. As part of this, consumers could seek out alternatives to carnivorous fish such as molluscs that provide dietary and economic benefits at lower social, economic, and environmental costs. However, many consumers will always choose low-cost products, especially those in constrained economic circumstances and the onus should be largely on the industry - and the governments that give it licence to operate - to improve its performance.

Appendix 1 – Norway

Norway is the world's largest producer of Atlantic salmon producing 1.3 million tonnes in 2018 or 52% of the global production.[131] According to governmental plans, the production of farmed Atlantic salmon is set to grow five-fold by 2050[132] to meet expected increases in global demand.[133]

Economic costs

Historically, Norway has had ideal conditions for salmon farming but in recent years the industry has been plagued by high mortality rates, as the industry generates -and runs up against - increasing environmental pressures. In 2018, it is estimated that over 52 million salmon were lost (13% of production) for varying reasons including diseases/sea lice and associated treatments, pollution and escapes.[134]

Taking annual salmon losses and multiplying them by the salmon price for each year reveals the scale of the economic cost this represents. Table 18 shows the percentage lost each year and the relevant price.[135] As we can see, these mortalities result in a direct economic loss over the seven years of over USD$8 billion.

Table 18: Opportunity costs of mortalities in Norway

	2013	2014	2015	2016	2017	2018	2019
Total harvest (mt)	1,168	1,258	1,303	2,133	1,236	1,282	1,357
Mortalities (t)	127,347	145,969	177,255	309,375	180,508	164,096	196,809
Percentage losses	11%	12%	14%	15%	15%	13%	15%
Value of losses (MUSD)	855	983	940	2208	1343	1234	1409

It is interesting to note that reducing mortalities to 5.5% on salmon farms in Norway would represent an annual saving of over $892 million USD (based on 2019 volumes and prices).

Substantial amounts are also spent in efforts to minimise mortalities by combatting disease and parasite infestations. According to Nofima, treating sea lice cost Kr4.5 billion in 2017, or 475 million dollars.[136] This includes an estimated NOK1.5 billion on cleaner fish (based on a cost of NOK1.2 per Kg of salmon produced).[137] As the Norwegian Veterinary institute points out, disease costs the aquaculture industry enormous sums of money, results in poor fish-welfare, reflects poorly on the aquaculture industry and is environmentally unfriendly. Whilst more effective disease control will be costly, in the long run it will be more profitable and will lead the industry in a more sustainable direction.[138]

The final economic cost considered here is that of fishmeal and fish oil (FMFO). In 2016, the Norwegian salmon industry utilised 1.62 million tonnes of feed ingredients.[139] Soy protein concentrate accounted for 19% of the feed ingredients, marine protein sources accounted for 14.5% and marine oils, 10.4%. The remainder was made up of wheat and plant-based oils. This the equivalent of 245,050 tonnes of fishmeal and 175,760 tonnes

131 FAO (2019) The State of World Fisheries and Aquaculture **http://www.fao.org/state-of-fisheries-aquaculture**

132 Bailey, J. L., & Eggereide, S. S. (2020). Indicating sustainable salmon farming: The case of the new Norwegian aquaculture management scheme. *Marine Policy*, *117*, 103925.

133 Aanesen, M., & Mikkelsen, E. (2020). Cost-benefit analysis of aquaculture expansion in Arctic Norway. Aquaculture Economics & Management, 24(1), 20-42.

134 Nofima (2017) High lice costs, rising feed prices – and expensive land-based facilities **https://nofima.no/en/forskning/naringsnytte/high-lice-costs-rising-feed-prices-and-expensive-land-based-facilities/**

135 Data from Statistics Norway **https://www.ssb.no/en/fiskeoppdrett**

136 Nofima (2017) High lice costs, rising feed prices – and expensive land-based facilities **https://nofima.no/en/forskning/naringsnytte/high-lice-costs-rising-feed-prices-and-expensive-land-based-facilities/**

137 Nofima estimate of Kr1.2 per kg of salmon (based on 1.3 billion kg in 2018) **https://thefishsite.com/articles/counting-the-true-cost-of-combatting-sea-lice**

138 Norwegian Veterinary Institute (2018) Fish Health Report 2018 **https://www.vetinst.no/rapporter-og-publikasjoner/rapporter/2019/fish-health-report-2018**

139 Aas, T.S, et al. 2019. Utilization of feed resources in the production of Atlantic salmon (*Salmo salar*) in Norway: An update for 2016. Aquaculture Reports 2019, vol 15

of fish oil. In Table 19, we estimate the annual cost to Norwegian aquaculture of using marine fish sources.

Table 19: Cost of FMFO 2013-2019 (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Cost of FM	$435	$428	$403	$346	$342	$350	$369
Cost of FO	$335	$335	$324	$288	$249	$352	$270

Source: author' calculation drawing on data from Statistics Norway[140], the World Bank[141], EUMOFA[142], Ytrestøyl et al, 2015[143], Aas et al. 2019[144] and the FAO[145]

The use of marine ingredients has declined dramatically since 1990 when 90% of the feed was of marine origin.[146] This had decreased to 30% in 2013 down to about 25% today. The latest analysis that is available is for 2016 but it is expected that reductions have plateaued in the absence of new technologies as has happened with fish oil since 2013. As demand for seafood has increased, reductions in use have been offset leading to no overall net decrease. If this continues, then we would expect to see the use of marine ingredients increase five-fold by 2050 in line with expansion plans. Taking these costs together, we can see that mortalities and their treatment[147] as well as the use of FMFO in feed cost the industry over $4 billion USD in 2019.

The Norwegian Veterinary Institute (2018) have pointed to the paradox that while only a very few fish die due to salmon-lice infection, delousing (e.g., stress from handling) is an important cause of direct and indirect mortality both for farmed salmon and cleaner-fish, and has significant welfare implications. Mortalities are (at least in part) a direct function of fish welfare, we can conclude therefore that poor fish welfare has a direct economic risk for farmers and investors, as well as being a wider social problem; an issue that we will discuss in the next section.

Social costs

In this section, we consider two sources of social costs: fish welfare and community impacts on coastal communities in West Africa from which FMFO is sourced.

Fish welfare is increasingly taking on importance as an issue for consumers, including evidence of its importance to Norwegian consumers.[148 149] To estimate the social cost of fish welfare, we have based our calculations on a study of European consumers of their willingness to pay for higher welfare salmon.[150] European consumers were selected, as Europe is a major consumer of salmon exports from Norway. This research found that, all things considered, the average European consumer was willing to pay a price premium of 14% for salmon with higher welfare standards. In Table 20, we apply this to all European consumers of Norwegian salmon since 2013. As we can see, consumers were on average willing to pay a cumulative premium of $3.6 billion USD.

140 Statistics Norway 07516: Fish farming. Loss in fish for food production, by fish species (C) 1993 – 2019 **https://www.ssb.no/en/statbank/table/07516/tableViewLayout1/ https://data.imf.org/?sk=471DDDF8-D8A7-499A-81BA-5B332C01F8B9, https://data.imf.org/?sk=471DDDF8-D8A7-499A-81BA-5B332C01F8B9**

141 **https://www.indexmundi.com/commodities/?commodity=fish-meal&months=120&currency=eur**

142 **https://www.eumofa.eu/documents/20178/148316/MH+4+2019+EN_final.pdf/**

143 Ytrestøyl, T., Aas, T. S., & Åsgård, T. (2015). Utilisation of feed resources in production of Atlantic salmon (Salmo salar) in Norway. *Aquaculture*, *448*, 365-374.

144 Aas, T. S., Ytrestøyl, T., & Åsgård, T. (2019). Utilization of feed resources in the production of Atlantic salmon (Salmo salar) in Norway: An update for 2016. *Aquaculture Reports*, *15*, 100216.

145 FAO (2016) COMMODITY STATISTICS UPDATE Fishmeal and Fish oil **http://www.fao.org/3/a-bl391e.pdf**

146 Aas, T. S., Ytrestøyl, T., & Åsgård, T. (2019). Utilization of feed resources in the production of Atlantic salmon (Salmo salar) in Norway: An update for 2016. *Aquaculture Reports*, *15*, 100216.

147 Values uprated to 2019 prices using average Norwegian rate of inflation 1.25%

148 Sandøe, C. G. P. Who cares about fish welfare? -A Norwegian study: Kristian Ellingsen Kristine Grimsrud Hanne Marie Nielsen Cecilie Mejdell Ingrid Olesen Pirjo Honkanen Ståle Navrud.

149 Grimsrud, K. M., 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, 19-27.

150 Zander, K., & Feucht, Y. (2018). Consumers' willingness to pay for sustainable seafood made in Europe. Journal of international food & agribusiness marketing, 30(3), 251-275.

Table 20: WTP calculation for higher fish welfare (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Norway	$271	$374	$434	$629	$603	$649	$713

Source: author's own, based on data from comtrade[151]

This proxy value demonstrates that fish welfare is material to consumers. Although the valuation approach could potentially be criticised as being anthropomorphic, valuation is intrinsically a human endeavour meaning that value can only be ascribed to humans, hence the emphasis on human perception of welfare in this instance.

In 2016, 169,000 tonnes of feed were used in Norwegian salmon farming. Of this, 14.5% was fishmeal and 10.4% was fish oil (Nofima). Of this, 6% and 4% were sourced from West Africa. Mauritania was the main West African supplier of marine ingredients to Norway in 2019.

Mauritania has recently developed a fishmeal industry based on these small pelagics and it has shown strong growth since 2010 as a result of higher prices for marine ingredients.[152] It is argued that this is already impacting on regional stocks and that these are likely to increase as the fishmeal industry expands.[153] There is limited research, especially of a quantitative nature on the potential impacts of the expansion of this industry.

In 2018, Norway imported almost 8.4 thousand tonnes of fish oil from Mauritania, for use in the salmon farming industry. To estimate, the potential loss of value added, we compare the value added from canning (based on Moroccan data) with producing FMFO (29% and 10% respectively)[154] (see Table 21 for a list of the assumptions used). The total annual cost of diverting the 90% of this fish that is suitable for DHC to fish oil is over $1 million per year.

Table 21: Assumptions in social calculations for Mauritania

Assumptions	Values
Value added of fishing	903,000,000
% fleet pelagics	722,400,000
Fish produced	1,500,000
Value added of canning	29%
Tonnes of pelagics canned	139,000
Value added canning	209,496,000
Total FMFO production	172,000
Value added of FMFO	10%
Value added FMFO	72,240,000
Difference	137,256,000
Difference per tonne in USD	1268

151 **https://comtrade.un.org/**

152 Corten, A., Braham, C. B., & Sadegh, A. S. (2017). The development of a fishmeal industry in Mauritania and its impact on the regional stocks of sardinella and other small pelagics in Northwest Africa. Fisheries research, 186, 328-336.

153 Ibid.

154 Data are drawn from Greenpeace A Waste of Fish, CEIC **https://www.ceicdata.com/en/morocco/fish-production-consumption-and-processing/fish-processing-volume-fish-meal-and-fish-oil**, ITC trade map and Government of Mauritania **http://www.peches.gov.mr/IMG/pdf/rapport_finalcadre_d_investissement.pdf**

An alternative way of estimating the loss of value added is to estimate the direct and indirect loss of employment. Data are not currently available for Mauritania, but an estimate by Wijkström for Asia suggests that if bycatch were not being used for fish farming in Asia, it would hypothetically create between 8.1 and 10.2 million jobs in post-harvest activities and processing. This equates to a minimum of 5 jobs per tonne of fish or 44,255 jobs lost in the supply chain for fish oil sold to Norway. If we multiply this by the GDP per head for Mauritania ($1188), it gives us a total value of $55.5 million. Even when we subtract the value of the fish oil exports ($16.8 million), we are left with a loss of $37.5 million.

There are also concerns over the welfare of wild wrasse (cleaner fish) on fish farms. Wrasse require shelters for protection when at rest and from tides and currents; supplementary feeding when lice numbers are low; and care during farm operations such as grading, and moving salmon, and net cleaning.[155] However, mortality rates are very high. 23 million wild wrasse were caught in Norway in 2018 and 40% of these died in the same year. Due to a lack of data, it was not possible to include a valuation of wrasse welfare in the model.

Environmental costs

Finally, we consider environmental costs. The most notable of these are:

- Impacts on wild salmonid stocks
- Impacts on wild cleaner fish stocks
- Impacts on pelagic fish stocks
- Impacts of local pollution
- Carbon emissions

Local pollution

Liu et al. have estimated the PAC for Norwegian salmon farming and found it to be 3.5% of total salmon production.[156] These are based on 2010 and may be therefore a little out of date. On the other hand, algal blooms are a continuing (and perhaps worsening) problem for Norwegian aquaculture. In 2019, 8 million salmon were killed in an algal bloom in just a few days.[157] This prompted the Norwegian government to invest almost one million Euros in aquaculture research. Although the loss to farmers of about NOK4 million was widely reported, the environmental cost has received less attention. Table 22 details the annual pollution abatement cost. This equates to a total PAC of USD$1.4 billion since 2013.

Table 22: Estimate of annual pollution abatement cost

	2013	2014	2015	2016	2017	2018	2019
Norway	$140,489,766	$154,941,911	$164,633,692	$222,735,005	$228,342,307	$238,998,213	$252,350,165

Impacts on fish stocks

There are three means by which salmon farming impacts on fish stocks. Two of these have already been discussed: the use of pelagic fish and cleaner fish in fish feed and lice treatment respectively. The third is the impacts on wild salmon stocks. A report by Thorstad and Finstad (2018) found that it can lead to an average of 12–29% fewer adult wild salmon. Table 23 estimates the indirect value of forage fish use in FMFO in Norway.

155 Treasurer, J., & Feledi, T. (2014). The Physical Condition and Welfare of Five Species of Wild-caught Wrasse Stocked under Aquaculture Conditions and when Stocked in Atlantic Salmon, Salmo salar, Production Cages. Journal of the World Aquaculture Society, 45(2), 213-219.

156 Liu, Y., & Sumaila, U. R. (2010). Estimating pollution abatement costs of salmon aquaculture: a joint production approach. Land Economics, 86(3), 569-584.

157 Magra, I. (2019) Millions of Salmon in Norway Killed by Algae Bloom. *New York Times* Accessed online: **https://www.nytimes.com/2019/05/23/world/europe/salmon-norway-algae-bloom.html**

Table 23: Loss of value as a result of forage fish being used in FMFO in Norway 2013-2019

	2013	2014	2015	2016	2017	2018	2019
Norway	$16,676,986	$14,749,795	$20,827,399	$21,100,028	$20,592,863	$21,042,291	$20,621,445

These figures only considered ex-vessel prices of predator fish dependent on forage fish. However, this is very likely an underestimation of the full economic benefits of predator fish (e.g., downstream benefits or supply chains, through processors, distributors, and consumers. It also most likely underestimates wider ecosystem benefits to nonmarket predators, such as seabirds, seals and so on. As well as the existence value of these species discussed elsewhere, there can be additional economic benefits such as ecotourism revenue (whale watching, bird watching, etc.)[158] Froehlich et al. assess whether FMFO use can circumvent forage fish limits (e.g. through greater consistent inclusion of fish byproducts). They find that this is possible by the middle of the 21st century. However, global shifts towards more pescatarian diets will make this impossible and increase the requirement for long-term, nutrient equivalent feed sources.[159]

As discussed above, salmon farms cause damage to wild salmon stocks through local pollution and the spreading of lice and disease. In addition, escaped salmon breed with local populations and their offspring are genetically less likely to survive and research suggests that these effects are likely to last down the generations.[160] Rates of returning salmon in Norway are less than half what they were in the 1980s[161] According to the Norwegian Scientific Committee on the Atlantic Salmon, the largest declines are seen in western and middle Norway, and negative impacts of salmon farming have contributed to this. Escaped farmed salmon are the primary threat to wild salmon followed by salmon lice and infections. They also argue that the present level of mitigation measures is too low to stabilize and reduce the threat. Impacts on escaped salmon are difficult to model but it is estimated that lice from salmon farms kill 50,000 wild salmon per year.[162] We know that returning salmon are about half a million fewer than in the 1980s.[163] If we conservatively assume about 150,000 of these are as a result of salmon farming (we know 50,000 are due to lice infestations, and assume 75,000 are due to hybridisation and 25,000 due to infectious diseases). This is about 30% of the lost wild salmon population. No studies were identified on Norwegian valuations of salmon conservation but we have taken an average of three figures per household from Canada, the UK and Ireland ($10, $20 and $18 respectively).[164] These represent the amount households would be willing to pay to restore salmon stocks. Applying the average of these to the lost salmon stocks gives us an annual figure of $11 million USD. We would suggest that this is a reasonable proxy for the value destroyed in Norwegian society by farmed fish impacts on wild populations.

158 Koehn, L. E., Essington, T. E., Marshall, K. N., Sydeman, W. J., Szoboszlai, A. I., & Thayer, J. A. (2017). Trade-offs between forage fish fisheries and their predators in the California Current. ICES Journal of Marine Science, 74(9), 2448-2458.

159 Froehlich, H. E., Jacobsen, N. S., Essington, T. E., Clavelle, T., & Halpern, B. S. (2018). Avoiding the ecological limits of forage fish for fed aquaculture. Nature Sustainability, 1(6), 298-303.

160 Hindar, K., Fleming, I. A., McGinnity, P., & Diserud, O. (2006). Genetic and ecological effects of salmon farming on wild salmon: modelling from experimental results. *ICES Journal of Marine Science*, *63*(7), 1234-1247.

161 Norwegian Scientific Advisory Committee for Atlantic Salmon (29019) Status of wild Atlantic salmon in Norway 2019 Accessed online: **https://www.vitenskapsradet.no/Portals/vitenskapsradet/Pdf/Status%20of%20wild%20Atlantic%20salmon%20in%20Norway.pdf**

162 Castle, S. (2017) As Wild Salmon Decline, Norway Pressures Its Giant Fish Farms *New York Times* https://www.nytimes.com/2017/11/06/world/europe/salmon-norway-fish-farms.html

163 Norwegian Scientific Advisory Committee for Atlantic Salmon (29019) Status of wild Atlantic salmon in Norway 2019 Accessed online: **https://www.vitenskapsradet.no/Portals/vitenskapsradet/Pdf/Status%20of%20wild%20Atlantic%20salmon%20in%20Norway.pdf**

164 Myrvold, K. M., Mawle, G. W., Andersen, O., & Aas, Ø. (2019). The Social, Economic and Cultural values of wild Atlantic salmon: A review of the literature for the period 2009-2019 and an assessment of changes in values. Lillehammer: Norwegian Institute for Nature Research.

The final wild fish impact is on wrasse stocks. However, these impacts are much ignored in the literature and could not be incorporated into this analysis. This is concerning, especially considering that surveys done by NTNU Social Research reveal that fish farmers question whether cleaner fish are an effective delousing method that actually results in fewer delousing operations.[165]

The aquaculture industry is often positioned as a sustainable alternative to land-based animal farming. However, as critics have pointed out, this is often based on flawed analysis that does not take into account the full CO^2 costs of salmon farming. Sintef have estimated the full CO^2 emissions for Norway taking account of previously uncounted impacts. These include the impacts of the use of soy in fish feed and its impact on deforestation in Brazil (all of the Norway's soy is sourced in Brazil). It also takes account of air freight in the distribution of salmon, which is increasing due to the increased importance of China as a consumer of Norwegian salmon. The total carbon emissions produced by the sector are 9.685 million tonnes. There are various methods for costing carbon emissions, and a wide literature on the appropriate valuations to use. If we conservatively use the carbon tax applied by Norway to fishing to this figure ($27 USD per tonne) we get an annual value of $255 million per year.[166] However, this value is substantially higher when a social cost of carbon is applied. Table 24 shows the emissions costs based on the Norwegian LCA data and using the UK's Department for Climate Change estimate of USD$72 per tonne ($5.2 billion).

Table 24: Emissions costs (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Norway	$626	$ 674	$699	$1,144	$663	$687	$728

Conclusion

A summary of the costs included in this study is provided in Table 25. As we can see, this analysis gives us a total cost since 2013 of almost USD$28 billion.

Table 25: Summary of costs (MUSD)

	Norway
Mortalities	8908
Lice	2142
FMFO	4832
Total economic cost	**15969**
Salmon stocks	52
Pelagic fish stocks	665
Local pollution	2328
Climate change	5224
Total environmental cost	**8269**
Fish welfare	3675
Total social cost	**3675**
Total	**27913**

165 The Norwegian Institute of Marine Research is also concerned about the method's lack of documented effectiveness. **https://norwegianscitechnews.com/2020/04/cleaner-fish-being-sacrificed-in-the-fight-against-salmon-lice/**

166 Bruvoll A. and Dalen H. (2009) Pricing of CO^2 emissions in Norway. Accessed online: **https://www.ssb.no/a/english/publikasjoner/pdf/doc_200916_en/doc_200916_en.pdf**

Appendix 2 – Scotland

Although Scotland's share of total salmon production is small relative to Norway and Chile (7.6%), it is an extremely important industry to the economies of both Scotland and the UK. It is currently the UK's biggest food export (in 2019 94,300 tonnes was exported to 54 countries, an increase of 26 per cent on 2018 figures)[167] and it is also valued by UK consumers (60% of production is consumed domestically).

The industry has grown by 91% since 1997 and is dominated by six large companies controlling 99% of the market.[168] In addition, the industry has widely publicised plans to grow further, with a target of increasing growth by another 100-165% from a 2018 baseline by 2030.[169]

Economic losses

Salmon deaths are reported by fish farming companies and published online by the Scottish Environment Protection Agency. In 2013, the Scottish government stopped publishing aggregate figures on mortalities, allegedly as a result of industry pressure.[170] Analysis of deaths reported to the SEPA by Inside Scottish Salmon Feedlots (ISSF) suggest a large increase in mortalities since 2002 (an increase from 3.1% to 13.5%). The main causes of deaths reported are infections, algal blooms, and delousing treatments.

To estimate the economic losses of these mortalities, we have taken the proportion of mortalities as a share of total farmed salmon production for Scotland in each year studied (base on FAO data).[171] Production has increased by 16% since 2013. However, losses have also increased by 60% over that period, as has the value of those losses. Cumulatively, this equates to 134,727 tonnes of salmon with a value of $922 million. Had mortalities been maintained at 6.4% since 2013, this would have represented a cumulative saving to the industry of almost $400 million. However, if survival rates similar to 2002 could be regained (about 97%), this will represent a cumulative saving of $668 million over the period

Table 26: Opportunity costs of Scottish mortalities 2013-2019[172]

	2013	2014	2015	2016	2017	2018	2019
Total harvest (mt)	160	179	170	163	189	156	190
Mortalities (t)	10,329	16,046	18,302	22,245	25,460	16,573	25,772
Percentage losses	6.40%	9.00%	10.80%	13.60%	13.40%	10.60%	13.50%
Value of losses (MUSD)	$67	$106	$97	$158	$189	$124	$177

To estimate the damage control cost of lice, we take an estimate derived by Costello (2009) for Scotland.[173] This was €0.25 per kg of salmon produced, based on 2006 production and prices. We have uprated this based on the UK inflation rate and convert to dollars (see Table 27). These costs are multiplied by the total amount of salmon produced in each of the years, giving a cumulative cost of $463million, or 6.7% of total sales, which is comparable with Costello's estimate for the global cost of sea lice (6%).

167 Scottish Salmon (2020) Scottish salmon exports explained **https://www.scottishsalmon.co.uk/facts/business/scottish-salmon-exports-explained#:~:text=Scottish%20salmon%20is%20both%20Scotland's,per%20cent%20on%202018%20figures**.

168 Marine Scotland Science (2018) Scottish fish farm production survey 2018 **https://www.gov.scot/publications/scottish-fish-farm-production-survey-2018/**

169 Feedback (2019) Fishy business Accessed Online **https://feedbackglobal.org/wp-content/uploads/2019/06/Fishy-business-the-Scottish-salmon-industrys-hidden-appetite-for-wild-fish-and-land.pdf**

170 Edwards, R. (2020) Farmed salmon deaths from disease reach record high **https://theferret.scot/farmed-salmon-deaths-disease-reach-record-high/#:~:text=%E2%80%9CMass%20mortalities%20are%20a%20function,commercially%20damaging%20for%20salmon%20farmers**

171 **http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en**

172 Data not available for 2019, calculation based on tonnage of mortalities multiplied by the global salmon price for 2019 **https://www.imf.org/en/Research/commodity-prices**

173 Costello, M. (2009). The global economic cost of sea lice to the salmonid farming industry. Journal of fish diseases, 32(1), 115.

Table 27: Estimate of cost of lice treatment in Scotland 2013-2019 (USD)

Year	Cost per kg Scotland	Total cost Scotland
2013	$0.36	$57
2014	$0.37	$66
2015	$0.37	$62
2016	$0.37	$60
2017	$0.40	$75
2018	$0.40	$62
2019	$0.41	$78

It is not clear if the Costello estimates included include the costs of over 1.5 million farmed cleaner fish[174] and about 30,000 wild caught wrasse,[175] used in Scottish salmon farming annually. The financial costs of cleaner fish have been increasing and are likely to be significantly higher than when Costello's estimates were derived.[176]

Scottish salmon contains a higher quantity of marine ingredient in its feed, and indeed is marketed on this basis.[177] Data on FMFO content in feed is available for 2014,[178] and these have been utilised to create estimates for 2013 and the intervening years. We know in that year that 25% of the 220,000 tonnes of feed utilised was fish meal and 15% was fish oil. Given that Scotland continues to have a higher proportion of marine content in its feed (some of its labels are as high as 51%)[179], we believe that this is unlikely to have decreased significantly in the intervening years. Estimates are based therefore on the ratio of FMFO to production in 2014 and the cost of feedstuffs, and result in a cumulative figure of USD$859 million (Table 3).[180]

Table 28: Cost estimates FMFO in Scottish salmon farming (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Scotland FM cost	$64	$70	$66	$62	$71	$58	$70
Scotland FO cost	$61	$63	$56	$51	$51	$57	$50

Social costs

Although Scottish salmon is promoted in the UK as a local product, and a good employer of local people a closer look at the numbers tells a different story. First, fewer than 25% of feedstuffs originate in the UK,[181] with most of the marine ingredients coming from Peru. Peru is the top exporter of fishmeal and fish oil (FMFO) worldwide and landings of anchoveta are used nearly exclusively for FMFO production, despite a proactive national food policy aimed at favouring their direct human consumption in an effort to tackle Peru's substantial undernutrition problem.[182]

Second, only about 2,000 people are directly employed by salmon farms. Even if we consider the 10,000 employed through the supply chain, this falls far short of the proportion employed in the tourism sector.[183] Scottish government data suggest that

174 Open Seas (2017) Cleaning up the 'cleaner fish'. Accessed online: **https://www.openseas.org.uk/news/cleaning-up-the-cleaner-fish/**

175 Scottish Salmon Search for wild wrasse. Accessed online **https://www.scottishsalmon.co.uk/search/pages?keys=wild%20wrasse**

176 Open Seas (2017) Cleaning up the 'cleaner fish'. Accessed online: **https://www.openseas.org.uk/news/cleaning-up-the-cleaner-fish/**

177 Feedback (2019) Fishy business Accessed Online **https://feedbackglobal.org/wp-content/uploads/2019/06/Fishy-business-the-Scottish-salmon-industrys-hidden-appetite-for-wild-fish-and-land.pdf**

178 Shepherd J, Monroig O & Tocher DR (2017) Future availability of raw materials for salmon feeds and supply chain implications: the case of Scottish farmed salmon, Aquaculture, 467, pp. 49-62.

179 Ibid.

180 World Bank, FAO and EUFMA

181 Newton, R. W., & Little, D. C. (2018). Mapping the impacts of farmed Scottish salmon from a life cycle perspective. The International Journal of Life Cycle Assessment, 23(5), 1018-1029.

182 Fréon, P., Sueiro, J. C., Iriarte, F., Evar, O. F. M., Landa, Y., Mittaine, J. F., & Bouchon, M. (2014). Harvesting for food versus feed: a review of Peruvian fisheries in a global context. Reviews in Fish Biology and Fisheries, 24(1), 381-398.

183 Schweisforth, L. (2018) The tragic demise of Scotland's salmon **https://sustainablefoodtrust.org/articles/the-tragic-demise-of-scotlands-salmon/**

this industry supports 218,000 jobs (the best estimate for the salmon industry is less than 5% of this).[184] Moreover, Scottish salmon farming reflects the concentration we see in the wider industry with most production being controlled by non-domiciled companies (see Table 29).

Table 29: Ownership of Scottish salmon farms

Company	Majority ownership
Cooke Aquaculture	Canadian
Grieg	Norwegian
Mowi	Norwegian
Loch Duart	USA
Scottish Sea Farms	Norwegian
Scottish Salmon Company	Ukraine

The UK, alongside some of the Nordic countries, has some of the strongest animal welfare legislation in the world,[185] reflecting perhaps the importance placed by UK consumers on animal welfare. Research has found that these concerns are top of the list for consumers when assessing how ethical they regard food and drink companies to be.[186] However, as discussed elsewhere fish welfare is a shared value across the European Union (EU). 52% of Scottish salmon is consumed domestically and of the 38% that is exported, 56% of that goes to the EU.[187] We can expect high fish welfare standards to appeal to these consumers. On average, research has found a WTP of 14% amongst European consumers. When we apply this to the 79% of salmon consumed in the UK/EU, we find that the total value for higher fish welfare is $902 million over the seven years (Table 30).

Table 30: Fish welfare premium for Scottish and EU consumers (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Scotland	$117	$130	$107	$114	$149	$136	$145

Environmental impacts

To value the environmental cost of local pollution in Scotland, we can also use data gathered via the contingent valuation method. A study by Whitmarsh et al. found that 76% of respondents in Scotland were in principle willing to pay a price premium (22%) for salmon produced using a method that caused only half the amount of nutrient discharge.[188] Public support for environmentally sustainable salmon has been found in several other studies. However, research also suggests that findings vary depending on factors like area deprivation and proximity to areas where salmon farming is providing jobs.[189] Nonetheless, there is growing evidence that, on average, increased concern over the environmental performance of the salmon farming industry is associated with a lower propensity to purchase salmon, and is therefore potentially damaging to the long-term profitability of the industry.[190] There is also evidence of support in the UK for alternative feeds such as the use of insect meal, especially when consumers

184 https://www.sdi.co.uk/key-sectors/tourism#:~:text=across%20the%20globe.-,The%20tourism%20sector%20in%20Scotland%20supports%20the%20jobs%20of%20218%2C000,that%20number%20is%20growing%20quickly

185 Evidence Group (2018) FARM ANIMAL WELFARE GLOBAL REVIEW SUMMARY REPORT https://www.nfuonline.com/nfu-online/sectors/animal-health/farm-animal-welfare-global-review-summary-report/

186 Farmers Weekly (2015) Animal welfare tops list of consumers' ethical concerns https://www.fwi.co.uk/livestock/health-welfare/animal-welfare-tops-list-consumers-ethical-concerns

187 https://www.bbc.com/news/uk-scotland-scotland-business-51460893

188 Whitmarsh, D., & Palmieri, M. G. (2009). Social acceptability of marine aquaculture: The use of survey-based methods for eliciting public and stakeholder preferences. Marine Policy, 33(3), 452-457.

189 Whitmarsh, D., & Palmieri, M. G. (2009). Social acceptability of marine aquaculture: The use of survey-based methods for eliciting public and stakeholder preferences. Marine Policy, 33(3), 452-457.

190 Maesano, G., Carra, G., & Vindigni, G. (2019). Sustainable dimensions of seafood consumer purchasing behaviour: A review. Calitatea, 20(S2), 358-364.

are educated on the benefits [191] Using data from the Whitmarsh study, enables us to estimate the willingness of consumers to pay for salmon reared to higher environmental standards. To be conservative, we have limited this calculation to UK consumers, as the data used is drawn from a Scottish survey (see Table 31). This results in a $655 million cost over the seven years. Separate calculations using Pollution Abatement Cost approach have been used in the main body of the report.

Table 31: Willingness to pay for higher environmental standards 2013-2019 (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Scotland	$85	$95	$78	$83	$109	$99	$105

As discussed above, forage fish provide a range of ecosystem services that are external to the market value of the fish themselves. Measuring these benefits holistically is challenging given the interconnected and complex nature of the marine ecosystem. One proxy that we can consider is the economic value of predators that depend on forage fish for their survival. The economic value of this is estimated at 11.3 billion globally, or $219 per tonne (based on global landings of 51.5 million tonnes). In Scotland, 460,000 tonnes of forage fish are required to produce around 179,000 tonnes of salmon[192]. This is a ratio of about 2.6:1. If we apply this ratio to Scottish landings since 2013, we can estimate the volume of forage fish consumed by the industry each year and apply our wild to farmed fish ratio. The results are displayed in Table 32. The cumulative ecosystem loss is estimated to be in the region of $680 million. However, as discussed elsewhere, this potentially grossly underestimates the full ecosystem/existence value, as it does not include non-market prey such as seals and seabirds, not to mention the economic value of marine tourism.[193]

Table 32: Ecosystem value of forage fish used in Scottish salmon production (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Scotland	$90	$100	$95	$91	$106	$87	$107

Worryingly, if traditional feed formulations have plateaued in terms of reducing FMFO, then we would expect the absolute number of wild caught fish to increase dramatically in line with plans to expand production. In the case of Scotland, this would mean doubling the volume of wild caught fish by 2020.

Scottish government data show that over 3.5 million salmon have escaped from salmon farms since 1990 when records began. Of these, fewer than 100,000 have been recovered, suggesting an annual net figure of about 289,000 per year. In August of this year, Mowi Scotland confirmed 48,834 escapes from just one facility. There are concerns about the impacts of escaped salmon on the wild population through infectious diseases, lice and interbreeding.[194] In response to this event, Fisheries Management Scotland has launched a research project on wild salmon genetics to gauge the impact of any interbreeding between wild and farm-raised salmon. We also know that salmon stocks have seen dramatic declines. The total rod catch for 2018 was the lowest on record and under 50% of the average for the period 2000-09.[195] Research by Scottish Enterprise has documented the negative economic effects of declining salmon stocks on rural businesses in Scotland.[196] Rod catches are only part of the story, and there is

191 Popoff, M., MacLeod, M., & Leschen, W. (2017). Attitudes towards the use of insect-derived materials in Scottish salmon feeds. Journal of Insects as Food and Feed, 3(2), 131-138.

192 Feedback (2019) Fishy business Accessed Online **https://feedbackglobal.org/wp-content/uploads/2019/06/Fishy-business-the-Scottish-salmon-industrys-hidden-appetite-for-wild-fish-and-land.pdf**

193 Koehn, L. E., Essington, T. E., Marshall, K. N., Sydeman, W. J., Szoboszlai, A. I., & Thayer, J. A. (2017). Trade-offs between forage fish fisheries and their predators in the California Current. ICES Journal of Marine Science, 74(9), 2448-2458.

194 Ford, J. S., & Myers, R. A. (2008). A global assessment of salmon aquaculture impacts on wild salmonids. PLoS Biol, 6(2), e33.

195 Scottish Enterprise (2019) INVESTIGATION INTO THE IMPACT OF DECLINE IN SALMON NUMBERS ON RURAL BUSINESSES **http://fms.scot/wp-content/uploads/2019/11/Fraser-Associates-Impact-of-Decline-in-Salmon-Numbers-on-Rural-Businesses-Final-Draft-11-09-19-1.pdf**

196 Ibid.

a similar finding for returning salmon, the stocks of which have more than halved in the 20 years to 2016 to just over a quarter of a million. As with our Norway estimates, if we assume that 20% of these are due to salmon farming impacts, we arrive at an estimate of 71,000 wild salmon being lost to fish farming each year. Using the same methodology as for Norway, we estimate a WTP to restore wild salmon stocks in Scotland of $48 million at the household level. A fifth of this cost gives us an annual cost to Scottish society of $15 million, or $68 million cumulatively (see Table 30).[197]

Table 33: WTP estimates for restoration of salmon stocks

	2013	2014	2015	2016	2017	2018	2019
Scotland	$9,601,368	$9,664,056	$9,719,772	$9,784,684	$9,850,944	$9,909,100	$9,982,492

Finally, we consider CO^2 emissions. Whilst the farmgate emissions from aquaculture are low relative to agriculture (one estimate for the UK is 324748 tonnes of CO^2relative to over 9 million tonnes respectively, or about 3.5%), these estimates underestimate the true carbon cost of aquaculture once airfreight and feedstuffs are considered. As demonstrated for Scotland, salmon is not a truly local product but supports a vast global value chain.[198] If we assume a similar carbon footprint to Norwegian salmon based on Life Cycle Analysis (7.45 kg per kg), we find a cumulative cost $288 million over the seven year period (Table 34).

Table 34: Estimates of CO^2 emissions from Scottish salmon farms

	2013	2014	2015	2016	2017	2018	2019
Scotland	$37,725,689	$41,350,373	$31,568,216	$40,728,203	$49,427,534	$41,089,631	$46,143,572

In conclusion, we can see that there are substantial private and external costs from salmon farming that are not usually quantified and or monetised.

Conclusion

A summary of the costs included in this study is provided in Table 35. As we can see, this analysis gives us a total cost in the seven years to 2019 of almost USD$4.6 billion.

Table 35: Summary of costs (MUSD)

	Scotland
Mortalities	*922*
Lice	*463*
FMFO	*859*
Total economic cost	**2233**
Salmon stocks	*68*
Pelagic fish stocks	*680*
Local pollution	*288*
Climate change	*425*
Total environmental cost	**1461**
Fish welfare	*902*
Total social cost	**902**
Total	**$4,596**

197 Household data taken from **https://www.nrscotland.gov.uk/statistics-and-data/statistics/statistics-by-theme/households/household-estimates/2019**

198 Newton, R. W., & Little, D. C. (2018). Mapping the impacts of farmed Scottish salmon from a life cycle perspective. The International Journal of Life Cycle Assessment, 23(5), 1018-1029.

Appendix 3 – Canada

Canada has 25% of the entire world's coastline.[199] This, along with its cold waters and access to the US market, mean that its salmon farming industry is considered to have significant potential for growth.[200] Fisheries and Oceans Canada also report that aquaculture (of which Atlantic salmon is about 75%) generates substantial growth and employment opportunities in rural areas.[201] However, it has also come under increasingly intense public scrutiny over its environmental impact, First Nations territorial rights and impacts on wild salmon.[202] An independent Auditor's Report in 2018 found that Fisheries and Oceans Canada had made insufficient progress on a range of indicators such as risk assessment for disease, auditing of fish health, impact assessment of the use of drugs or pesticides on wild fish and measures to minimise escapes.[203] These concerns may partly explain why Canada has not seen the growth experienced by competitors, with 2019 seeing a 2% fall in production.[204] In response to criticisms, the Canadian Government has been researching and investing in new technologies, such as land based RAS and hybrid systems, IMTA systems[205] and specifically identifies systems that offer the best combination of environmental, social, and economic performance.[206] Indeed, the Liberal party's last manifesto included a pledge to shift all production to land-based systems, as well as introduce the country's first aquaculture act.[207]

Economic costs

Production figures have been accessed through Statistics Canada. However, these were not available for 2019, and have been calculated based on an FAO study that reported that production fell by 2% in Canada in 2019.[208] Unfortunately, Canada does not publish annual mortalities data. Although monthly mortalities data are available, production data are published annually, which makes it impossible to ascertain absolute mortalities. In this study, we have taken the average for Norway and Scotland and applied it to Canada. This may well overestimate Canada's mortalities but in the absence of official data, this is the most plausible assumption. If this is inaccurate, we would encourage the Ministry of Oceans and Fisheries to publish these data. Table 36 displays the calculations based on these data. As we can see, there is a total cost to Canadian farmers of USD$768 million.

Table 36: Opportunity costs of mortalities in Canada 2013-2019

2013	2014	2015	2016	2017	2018	2019
$53	$59	$81	$143	$147	$130	$152

There have been a few attempts to estimate the cost of sea lice to salmon farms in Canada.[209] Based on 2000 prices, Mustafa et al. estimate that the total cost to salmon farmers was $0.56/kg of salmon when the full costs such as reduced growth and feed conversation ratio. Costello (2006) builds on these to develop global estimates for

199 Flaherty, Mark, et al. "Public attitudes towards marine aquaculture in Canada: insights from the Pacific and Atlantic coasts." Aquaculture International 27.1 (2019): 9-32.

200 **https://www.oag-bvg.gc.ca/internet/English/parl_cesd_201804_01_e_42992.html**

201 **https://www.dfo-mpo.gc.ca/aquaculture/sector-secteur/socio/index-eng.htm**

202 Britten, L. (2019) B.C. First Nation sues feds over Atlantic salmon farming in Pacific waters **https://www.cbc.ca/news/canada/british-columbia/bc-salmon-farming-lawsuit-1.4976042**

203 **https://www.oag-bvg.gc.ca/internet/English/parl_cesd_201804_01_e_42992.html**

204 FAO (2020) Salmon's upward growth trajectory grinds to a halt over COVID-19 **http://www.fao.org/in-action/globefish/market-reports/resource-detail/fr/c/1296665/**

205 In IMTA, species from different trophic levels are raised in proximity to one another with the organic and inorganic wastes of one cultured species serving as nutritional inputs for others. IMTA has been shown to reduce benthic ecological impacts in proximity to Atlantic salmon farms, improve social perceptions of aquaculture, and provide potential financial benefits for aquaculture producers via product diversification, faster production cycles, and price premiums for IMTA products

206 **https://www.dfo-mpo.gc.ca/aquaculture/publications/ssat-ets-eng.html#toc-6**

207 The Fish Site (2019) Canadian farmers lambast "irresponsible" Liberal call for land-based salmon farming https://thefishsite.com/articles/canadian-farmers-lambast-irresponsible-liberal-call-for-land-based-salmon-farming

208 FAO (2020) Salmon's upward growth trajectory grinds to a halt over COVID-19 **http://www.fao.org/in-action/globefish/market-reports/resource-detail/fr/c/1296665/**

209 Pike, A. W., & Wadsworth, S. L. (1999). Sea lice on salmonids: their biology and control. In Advances in parasitology (Vol. 44, pp. 233-337). Academic Press. and Mustafa, A., Rankaduwa, W., & Campbell, P. (2001). Estimating the cost of sea lice to salmon aquaculture in eastern Canada. The Canadian veterinary journal, 42(1), 54.

Canada.[210] To avoid double counting with mortalities, we have used treatment costs alone, estimated at €0.10 per kg for Canada. This figure has been uprated to 2019 prices using average inflation in Canada since 2006,[211] and converted to USD. Table 37 displays the results. As we can see, the cumulative costs are USD$111 million.

Table 37: Costs of sea lice treatment in Canada 2013-2019 (MUSD)

Year	Cost per kg Canada	Total cost Canada
2013	0.112	$12
2014	0.114	$11
2015	0.116	$16
2016	0.117	$17
2017	0.119	$17
2018	0.122	$17
2019	0.125	$17

Canada has historically relied less on cleaner fish to tackle sea lice. A lumpfish hatchery is currently seeking approval to produce up to 3 million lumpfish.[212] However, it has been stalled in 2020 by environmental reviews. Nonetheless, cleaner fish are increasingly seen a solution to Canada's sea lice problem.

Canada has historically used a lower proportion of marine ingredients in its aquafeed than competitors.[213] In 2013, Sarkar et al.[214] report these as 15-18% for fish meal and 12-13% for fish oil in 2013. This is down from 20–25% and 15–20% in 2005. Averages of the 2013 figures 16.5% and 12.5% have been used to estimate the cost of feed ingredients of marine origin to salmon farmers in Canada (Table 38). Cost of total feed estimates were drawn from Statistics Canada and the FAO. The cumulative cost of the use of fish feed is USD$454.

Table 38: Cost of FMFO in Canada 2013-2019 (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Canada FM cost	$23	$30	$36	$35	$37	$41	$40
Canada FO cost	$19	$26	$30	$29	$32	$35	$34

210 Costello, M. (2009). The global economic cost of sea lice to the salmonid farming industry. Journal of fish diseases, 32(1), 115.

211 **https://www.inflation.eu/en/inflation-rates/canada/historic-inflation/cpi-inflation-canada.aspx**

212 Khan, I (2019) Lumpfish to be grown in Canadian hatchery **https://www.fishfarmingexpert.com/article/lumpfish-to-be-grown-in-canadian-hatchery/#:~:text=An%20application%20to%20develop%20Canada's,has%20been%20put%20into%20motion.&text=The%20hatchery%20will%20produce%20three,sea%20lice%20off%20farmed%20salmon.**

213 Sarker, P. K., Bureau, D. P., Hua, K., Drew, M. D., Forster, I., Were, K., ... & Vandenberg, G. W. (2013). Sustainability issues related to feeding salmonids: a Canadian perspective. Reviews in Aquaculture, 5(4), 199-219.

214 Ibid.

Social costs

As discussed, negative public attitudes, especially on the Pacific coast of Canada have been a brake on the growth of aquaculture.[215] One study of 68 countries found that Canada had the highest proportion of negative sentiment towards all kinds of aquaculture, as well as the most polarized split between positive and negative opinions.[216] The strongest negative perceptions are held for salmon farming on both coasts.[217] As part of this, fish welfare is an emerging animal welfare concern in Canada. For the purposes of this study, it was not possible to uncover any studies that looked at fish welfare as a discreet sub-section of ethical/sustainable production. Instead, we have used the EU estimate used elsewhere (14%). This is plausible given that animal welfare standards are somewhat similar, and (as discussed) there is plenty of evidence that Canadians care about animal welfare. 85% of Canadian salmon exported to the US, where animal welfare legislation is less stringent. We have therefore limited our analysis to the 15% of salmon that is consumed domestically. This is multiplied by the fish welfare premium of 14%. The results are shown in Table 39. As we can see, there is a total cost of USD$97 million.

Table 39: Estimate of WTP for poor salmon welfare (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Canada	$9	$9	$10	$16	$16	$17	$17

The second social cost considered in the other analyses is the impacts on fishing communities in developing countries. Canada has a domestic FMFO industry and imports only small amounts from West Africa (160 tonnes) since 2013.[218] However, using the job loss estimates applied to Mauritania, we can see a loss to Senegal of $1.2 million. Canada also imports FMFO from Peru, where similar issues may arise but are out of scope for this study.

Environmental costs

To estimate the environmental costs, we have used data from studies that compare the use of IMTA technology with conventional salmon farming. IMTA consists of farming in proximity aquaculture species from different trophic levels and with complementary ecosystem functions. This strategy makes it possible for one species' uneaten feed and wastes, nutrients, and by-products to be recaptured and turned into fertilizer, feed, and energy for the other crops.[219] The findings from this study suggest that the introduction of the IMTA salmon would increase the average household of those that do not consume salmon of between $25.5 per year and around $51 per year for five years. Even in the most conservative estimate (e.g. where don't knows were treated as no), the estimates are between $3.42 and $5.22 per year. Using an average of these two most conservative estimates $4.32 and multiplying it by the number of households in Canada (based on the latest census data for that year),[220] gives us an aggregate welfare increase of USD$307 million (Table 40). An average of the less conservative estimate gives a value of $627 million. Separate calculations using Pollution Abatement Cost approach have been used in the main body of the report.

215 Flaherty, Mark, et al. "Public attitudes towards marine aquaculture in Canada: insights from the Pacific and Atlantic coasts." Aquaculture International 27.1 (2019): 9–32.

216 Froehlich, H. E., Gentry, R. R., Rust, M. B., Grimm, D., & Halpern, B. S. (2017). Public perceptions of aquaculture: evaluating spatiotemporal patterns of sentiment around the world. PloS one, 12(1), e0169281.

217 Flaherty, Mark, et al. "Public attitudes towards marine aquaculture in Canada: insights from the Pacific and Atlantic coasts." Aquaculture International 27.1 (2019): 9–32.

218 Greenpeace (2019) A Waste of Fish **https://www.greenpeace.org/international/publication/22489/waste-of-fish-report-west-africa/**

219 Martinez-Espiñeira, R., Chopin, T., Robinson, S., Noce, A., Knowler, D., & Yip, W. (2016). A contingent valuation of the biomitigation benefits of integrated multi-trophic aquaculture in Canada. Aquaculture economics & management, 20(1), 1-23.

220 **https://www150.statcan.gc.ca/n1/daily-quotidien/170913/t001a-eng.htm**

Table 40: WTP for use of IMTA production system in Canada (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Canada	$40	$40	$40	$46	$46	$46	$46

The indirect economic value of forage fish has been estimated at 11.3 billion globally, or $219 per tonne (based on global landings of 51.5 million tonnes). Data are not available on the FIFO ratio for Canada. Several authors have estimated FIFO ratios for forage fish to farmed salmon and estimated it to be around 5:1.[221] These data have been the subject of controversy however, and have been rebutted by other studies.[222] Both found lower estimates of FIFO (2:1 and 0.78:1 respectively). Canada has historically used fewer marine ingredients in its aquafeed than other countries, and we have chosen therefore to use the most conversative FIFO ratio of 0.78:1. Table 41 shows the tonnes of forage fish required to produce salmon in Canada and the associated annual cost. Cumulatively, the indirect cost of forage fish is $135 million.

Table 41: Estimate of indirect cost of use of forage fish in salmon farming 2013-2019 (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Canada	$16	$14	$20	$21	$20	$21	$20

Canadian government data show that almost 40,000 salmon have escaped from salmon farms in Canada since records began.[223] Canada is home to seven different species of Pacific salmon as well as the Atlantic salmon on its eastern seaboard. Both types of salmon have been experiencing a decades-long decline in returning stocks with 2019 being a particularly bad year for the Pacific salmon.[224] Findings on the impact of salmon farms on the wild population vary. One study that compared the survival of wild salmon that travel near farms to those that don't, finding that upward of 50 per cent of the salmon that pass by farms don't survive.[225] Other studies have found limited impact. According to Nasco, the Atlantic salmon has seen a 41% decline since the 1980s. In total, 436,000 salmon returned to Canadian rivers in 2019,[226] a decline of 627,415. If we assume 20% of this is because of salmon farming impacts (see Norway assumptions), this gives us a loss attributable to salmon farming of 188,244 salmon over the period. Using data from a Canadian study suggesting a USD$10 WTP per household, we can estimate that the conservation value over the seven-year period is $187 million (see Table 42).

Table 42: Welfare loss from depletion of salmon stocks attributable to aquaculture

	2013	2014	2015	2016	2017	2018	2019
Canada	$24,874,940	$24,874,940	$24,874,940	$28,144,160	$28,144,160	$28,144,160	$28,144,160

221 Tacon, A.G.L., Metien, M., 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. Aquaculture 285, 146–158 Welch, A., Hoenig, R., Stieglitz, J., Benetti, D., Tacon, A., Sims, N., & O'Hanlon, B. (2010). From fishing to the sustainable farming of carnivorous marine finfish. Reviews in Fisheries Science, 18(3), 235-247.

222 Byelashov, Oleksandr A., and Mark E. Griffin. "Fish in, fish out: Perception of sustainability and contribution to public health." Fisheries 39.11 (2014): 531-535.

223 **https://open.canada.ca/data/en/dataset/691dd994-4911-433d-b3b6-00349ba9f24e**

224 **https://www.pac.dfo-mpo.gc.ca/pacific-smon-pacifique/science/research-recherche/2019-summ-somm-eng.html**

225 Ford, J. S., & Myers, R. A. (2008). A global assessment of salmon aquaculture impacts on wild salmonids. PLoS Biol, 6(2), e33.

226 Atlantic Salmon Federation (2020) 2020 STATE OF WILD ATLANTIC SALMON REPORT **https://www.asf.ca/assets/files/asf-2020-state-of-population-v2.pdf**

As discussed elsewhere, life cycle analysis of carbon emissions shows that Norway has the lowest impacts per unit production, whereas impacts are consistently highest in the UK.[227] Several studies show that feed provision is the single most important contributor to resource use and emissions.[228] Carbon emissions have been estimated for Canadian salmon farms at 2,300 kg of CO^2 per tonne of salmon. However, as discussed in the main body of the report, these are farmgate emissions, which do not include emissions embedded in feedstuffs etc. Using the Norwegian LCA data and the UK's Department for Climate Change estimate of USD$72 per tonne, gives us an estimate for Canada of USD$425 million (see Table 43).

Table 43: Climate change costs in Canadian salmon farming 2013-2019 (MUSD)

	2013	2014	2015	2016	2017	2018	2019
Canada	$52	$46	$65	$66	$64	$66	$64

Conclusion

A summary of the costs included in this study is provided in Table 44. As we can see, this analysis gives us a total cost since 2013 of almost USD$2.3 billion.

Table 44: Summary of costs for Canadian salmon farming 2013-2019 (MUSD)

	Canada
Mortalities	$768
Lice	$111
FMFO	$454
Total economic cost	**$1333**
Salmon stocks	$187
Pelagic fish stocks	$135
Local pollution	$189
Climate change	$425
Total environmental cost	**$936**
Fish welfare	$97
Total social cost	**$97**
Total	**$2366**

227 Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., ... & Silverman, H. (2009). Not all salmon are created equal: life cycle assessment (LCA) of global salmon farming systems.

228 Ibid.

Appendix 4 – Chile

Although salmon is not a native species to Chile, the climate in the southern part of the country offers suitable conditions for salmon farming, which now represents the country's second largest export. As with other regions, the industry is seen as an important provider of jobs for people living in some of Chile's most remote communities. The Chilean aquaculture industry has grown significantly since the late 1980s, mainly farming salmon (Atlantic and coho) and trout.[229] According to Sernapesca, total harvest for these species was the highest on record in 2019, with total salmon production reaching 907,370 tonnes, worth $7.3 billion.[230] Chile is the second largest producer of salmon with a share of about 25% globally.[231]

In general, regulations in Chile are weaker than in the other three countries. For example, there are no regulations based on carrying capacity estimates to limit maximum fish biomass per area or water body[232] The level of antibiotics used in Chile's salmon farming industry is higher than in any other country in the world and is considered to have impacts on both animal welfare and the environment[233] Profitability and growth have also been damaged by a series of crises relating to pollution, escapes and mortalities. In 2016, the industry experienced a crisis when heaps of dead fish washed ashore in Chiloé, which according to Greenpeace, was caused by salmon companies throwing 9,000 tons of dead fish into the sea, which were consumed by other wildlife.[234] In 2018 nearly 700,000 were reported to have escaped into the wild and in 2020 the Marine Farm company notified SERNAPESCSA of an event that led to the death of ten thousand fish (43 tonnes) of fish because of an algal bloom.[235] In 2018 to boost production, rules were relaxed (salmon farmers are now able to increase stocking by up to 9% per cycle, up from 3%).[236] Although related to baseline fish health performance, this creates risks for further health and welfare problems.

Data on Chile are also far more limited and the impact of unintended outcomes is largely unquantified[237]. Production data have been accessed through Sernapesca. As with Canada, Chile does not publish annual mortalities data. Although monthly mortalities data are available, production data are published annually, which makes it impossible to ascertain absolute mortalities. In this study, we have taken the average for Norway and Scotland and applied it to Chile. We have no sense of how accurate this is for Chile but in the absence of official data, this is the most plausible assumption.

The costs of FMFO were estimated through by taking the total amount of feed used in salmon production, as reported in the 2019 salmon industry handbook. The data published are 2015-2018 and the missing years were extrapolated from those based on production statistics. There are two sources of data on FMFO in meal in Chile. The first is from the FAO[238] for 2010 (20-25% FM and 12% FO) and second is from the salmon industry

229 Quinones, R. A., Fuentes, M., Montes, R. M., Soto, D., & León-Muñoz, J. (2019). Environmental issues in Chilean salmon farming: a review. Reviews in Aquaculture, 11(2), 375-402.

230 Fish Farming Expert (2019) Chile harvested nearly 1m tonnes of salmonids in 2019 **https://www.fishfarmingexpert.com/article/chilean-salmonid-production-close-to-1-million-tonnes-in-2019/**

231 Iversen, A., Asche, F., Hermansen, Ø., & Nystøyl, R. (2020). Production cost and competitiveness in major salmon farming countries 2003–2018. Aquaculture, 522, 735089.

232 Quinones, R. A., Fuentes, M., Montes, R. M., Soto, D., & León-Muñoz, J. (2019). Environmental issues in Chilean salmon farming: a review. Reviews in Aquaculture, 11(2), 375-402.

233 Claudio Miranda, Felix Godoy and Matthew Lee, "Current Status of the Use of Antibiotics and the Antimicrobial Resistance in the Chilean Salmon Farms," *Frontiers in Microbiology,* June 18, 2018, **https://www.frontiersin.org/articles/10.3389/fmicb.2018.01284/ful**

234 Haggebrink, E. (2020) Chilean Aquaculture: Expansion into Troubled Waters? **https://www.sustainalytics.com/esg-blog/chilean-aquaculture-expansion-into-troubled-waters/#_edn3**

235 Mercopress, (2020) Massive mortality of Atlantic salmon species in south Chilean farms **https://en.mercopress.com/2020/04/16/massive-mortality-of-atlantic-salmon-species-in-south-chilean-farms**

236 Evans, O. (2018) New rules allow Chilean salmon farms to expand production by up to 9% **https://salmonbusiness.com/new-rules-allow-chilean-salmon-farms-to-expand-production-by-up-to-9/**

237 Poblete, E. G., Drakeford, B. M., Ferreira, F. H., Barraza, M. G., & Failler, P. (2019). The impact of trade and markets on Chilean Atlantic salmon farming. Aquaculture International, 27(5), 1465-1483.

238 Tacon, A. G., Hasan, M. R., & Metian, M. (2011). Demand and supply of feed ingredients for farmed fish and crustaceans: trends and prospects. FAO Fisheries and Aquaculture technical paper, (564), I.

handbook for 2017 (9% FM and 7% FO).[239] The intervening years have been estimated based on a linear decline. These data suggest that Chilean salmon farming has greatly reduced its reliance on wild fish since 2013. The results of these calculations are set out in Table 45. Using the same commodity prices used elsewhere in the report, we find a total cost to Chilean farmers since 2013 of just over USD$2 billion.

Table 45: FMFO calculations: Chile (2013-2019)

	2013	2014	2015	2016	2017	2018	2019	Total
Atlantic salmon (t)	492329	644459	608546	532225	614180.46	661138.39	701984	**4254862**
Feed (t)	997210	1312118.888	1239000	1038000	1196000	1289000	1368635	
%FM	17	15	13	11	9	9	9	
%FO	10	9	8	8	7	7	7	
FM (t)	166677	147445	128213	108981	89749	89749	89749	**820562**
FO (t)	98296	91174	84051	76928	69805	69805	69805	**559862**
Cost of FM (MUSD)	219	190	162	136	110	109	108	**1,037**
Cost of FO (MUSD)	205	176	151	130	102	139	101	**1,007**

For the remaining calculations, averages were generally used from other countries included in this analysis, and the details of these calculations have been set out in the main body of the report.

239 Mowi (2019) Salmon farming handbook, 2019 **https://ml.globenewswire.com/Resource/Download/1766f220-c83b-499a-a46e-3941577e038b**

justeconomics.co.uk