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Reducing carbon emissions in aquaculture: Using Carbon Disclosures to identify unbalanced mitigation strategies

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ABSTRACT

The production of Scottish Atlantic salmon (*Salmo salar*) involves a global supply chain with greenhouse gases (GHG) emitted at every step. With the UK government setting a net zero target by 2050, and the Scottish Government having committed to achieving net zero by 2045, the Scottish salmon aquaculture sector now needs to start to develop and implement comprehensive emissions reductions measures. The methods demonstrated here and the identified imbalances in carbon emissions mitigation strategies provide a route to support this process. We use two international aquaculture operators in Scotland, Grieg Seafood and Mowi, as case studies to understand the scale of GHG emissions in the industry, how these compare to mitigation strategies, and where reduction efforts should be focused. Environmental data disclosed to the Carbon Disclosure Project (CDP), which includes in-depth breakdowns of GHG emissions in Scope 1, Scope 2 and Scope 3 categories were used for the first time in this comparison. This was contrasted with interview data from academics, industry experts and NGOs to identify routes to the most effective mitigation and reduction strategy. CDP data successfully identify imbalances between GHG emissions and mitigation strategies, and demonstrate that while Scope 1 emissions in Scottish aquaculture operations are high compared to other countries, Scope 3 emissions represent the majority of emissions. In terms of mitigation, Scope 1 and Scope 2 strategies are adequate, but Scope 3 mitigation strategies do not match the scale of emissions, identifying a potential route for future carbon emission reductions.

1. Introduction

Seafood is a critical component of human livelihoods. It provides food security to the majority of the planet and contributes to the employment of millions, many in developing countries (FAO, 2018). Whilst global capture fisheries production has stagnated and even decreased, aquaculture has grown and now grows faster than any other food production sectors, with an average annual rate of 5.8% between 2000 and 2016 (FAO, 2018). In 2018, aquaculture accounted for 46% of total global fish production (FAO, 2020). Expansion of aquaculture is considered a potential solution to increased food and nutrition security, allowing seafood supply to match demand (Ellis et al., 2016). Given this, and the push by countries and businesses to reduce greenhouse gas emission (GHG), it is critical that expansion of this industry is done in a manner that is sustainable and carbon efficient.

Of the finfish farmed for consumption, salmon is of particular interest, as it is the largest single fish commodity in terms of value (FAO, 2018), whose growth in production exceeds that of aquaculture in general (Iversen et al., 2020). There are different species of salmon in aquaculture, but Atlantic Salmon (*Salmo salar*) is the key one considered in this study. Salmon aquaculture is the most developed form of intensive aquaculture, having experienced large productivity increases and technological change since the 1970s in Western Europe (e.g. Norway and Scotland (Shepherd et al., 2017)), and overall, 95.6% of total salmon production is from 5 countries; Norway (56.6%), Chile (25.4%), Scotland (7.6%) Canada (6%) and the Faroe Islands (3.3%) (Iversen et al., 2020).

1.1. A profile of Salmon Aquaculture in Scotland

Salmon aquaculture in Scotland largely takes place in open net pens off the West Coast of Scotland, the Hebrides, Orkney and Shetland (Fig. 1). The practice of salmon aquaculture in Scotland resembles practices around the world: the juveniles spend the first 18–22 months of their lives in freshwater, in tanks or pens located in lakes, until they are about 70–100 g (Newton and Little, 2018). Then, they are

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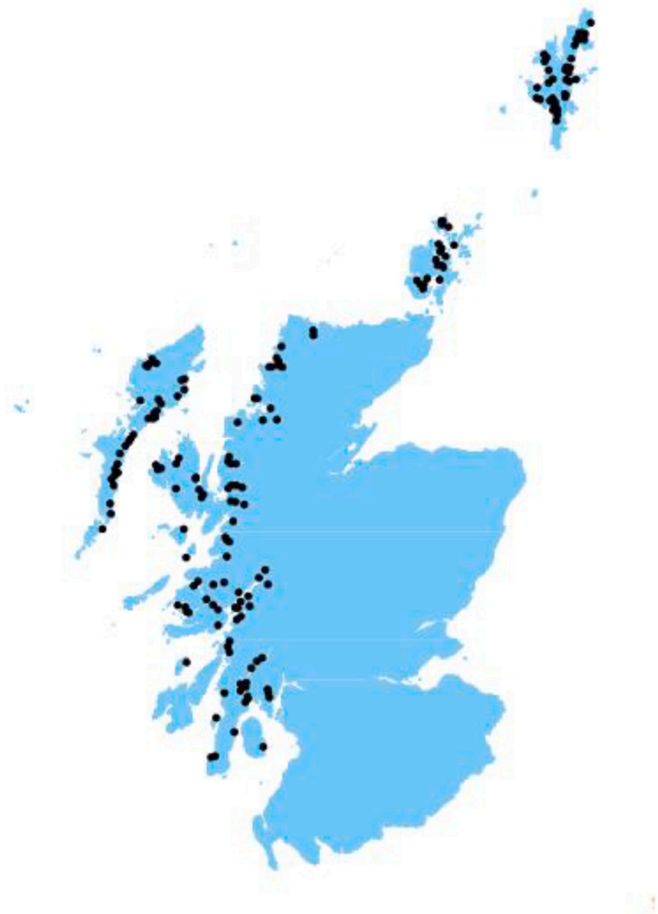

Fig. 1. The distribution of active Atlantic Salmon sites in Scotland in 2018 (Marine Scotland Science, 2018).

transferred to saltwater environments, close to shore or in sea lochs where they are reared for ca. 18 months until they reach 4.5 kg (Ford et al., 2012). They are then transported by well-boats from the pens to a slaughter station (Newton and Little, 2018). Scottish aquaculture accounts for the majority of the UK's aquaculture and there are plans to expand this production and double its value by 2030 (Collins et al., 2020).

Despite Scottish salmon production volumes being lower than other countries', it holds a distinct market position due to standards and certification. The Scottish industry focuses on animal welfare and high Omega-3 fatty acids which highlight the nutritious quality of the fish (Stevens et al., 2018). Scottish salmon aquaculture is dominated by 5 firms that are Norwegian (3), Canadian (1) and Faroese (1). The development of the industry has resulted in year-round availability of cheap salmon products as well as employment in remote locations on the West Coast and islands, generating economic and social benefits for some stakeholders (Shepherd et al., 2017), and imposing economic and social costs on others (Riddington et al., 2020).

1.2. Climate risks to salmon aquaculture

Like all intensive cultures, salmon aquaculture has impacts on the environment around it, but due to its practice of having open pens, it is also potentially susceptible to changes in environmental conditions. Whilst there is little evidence that Scottish aquaculture is presently being affected by climate change, the probability of impact to the industry in the future is significant (Callaway et al., 2012). As the industry depends on the marine environment for the provision of optimal biophysical conditions, ocean warming could impact productivity (Klinger et al., 2017). Mitigation of this has already been observed in North Atlantic fisheries shifting ranges northwards to optimum cooler temperatures (Perry et al., 2005). Rising temperatures could also facilitate the emergence, spread and virulence of parasites and pathogens (Callaway et al., 2012).

Given the importance of aquaculture and the need to reduce carbon emissions to meet Government objectives (here with a focus on Scotland with a Net Zero target by 2045, but applicable for many countries), it is critical that we are able to assess current supply and value chains against current and future mitigation plans. Without such measures it will be challenging for the sector to meet the Scottish Government's policy commitment in the 2021 Bute House Agreement to establish a sustainable aquaculture industry. The need for regulatory change is recognized in the 2022 Griggs Review of the Aquaculture Regulatory Process in Scotland which calls for an overhaul of the regulatory regime. Here we use publicly accessible data to critically assess GHG emissions from the salmon industry in Scotland to identify where future efforts may be best placed, and contrast this with interview data from various stakeholders to assess the feasibility and efficacy of any such mitigation strategies. To achieve this, and to provide a baseline for future emission reduction assessments, we 1) identify the most GHG-intensive step in the salmon farming process and its associated value chain, 2) explore the current GHG mitigation actions undertaken in Scottish salmon farms, and 3) assess whether carbon emissions mitigation actions match the scale of farming emissions.

2. Methods

This research relies on a multi-strategy design (McGhee et al., 2019), combining qualitative and quantitative data through existing literature, assessment of environmental data from two large aquaculture operators in Scotland, and interviews with experts and stakeholders in salmon aquaculture.

2.1. Analysis of environmental impact data

Two global aquaculture companies which operate in Scotland were chosen as examples: Mowi ASA and Grieg Seafood ASA (GSF).

Mowi ASA is the world's biggest producer of farmed salmon by revenue and volume, with a prediction of 450,000 gutted weight tonnes (GWT) of salmon for 2020, farming across Europe, North America and South America (Mowi, 2019). It is the largest producer of salmon in Scotland, with a production of 45,000 t gutted weight equivalent (GWE) in 2016 (Kenyon and Davies, 2018).

GSF ASA is also an international aquaculture operator, with farms in North America and Europe, targeting a harvest of 100,000 GWT for 2020 (GSF, 2020a). It has a Scottish operation in the Shetland Islands, and was the fifth largest salmon producer in Scotland in 2016 with a production of 13,500 t GWE (Kenyon and Davies, 2018). Both companies are Norwegian, headquartered in Bergen and listed on the Oslo Stock Exchange.

These two operators both disclosed environmental data to CDP (formerly known as Carbon Disclosure Project). This research uses the 2019 disclosure, relating to the year 2018. Once data is disclosed, companies receive a score which reflects their environmental actions. GSF was awarded an 'A' for its answers to the 2019 Climate Change questionnaire, making it onto the CDP A List, and Mowi was awarded an A-. The A to A- band indicates that the companies display good environmental management, and leadership relating to climate change mitigation (CDP, 2020a). The CDP climate change questionnaire evaluates 13 categories for environmental disclosure, including the company's risks and opportunities posed by climate change in the short and long term, the business strategy as a response to this, the company's targets and performance, yearly emissions data (with breakdowns), as well as a specific category dedicated for energy (CDP, 2020b). Data collected from the two case studies were assigned as Scope 1, Scope 2 and Scope 3, as categorised by the GHG Protocol accounting tool (see Supplementary Materials).

- Scope 1 emissions are directly released onsite or from sources controlled by the company resulting from fuel combustion, and incorporating accidental leakage (GHG Protocol, 2019).
- Scope 2 emissions are indirect resulting from the generation of energy purchased by the reporting company (World Resources Institute, 2015).
- Scope 3 emissions are also indirect emissions upstream or downstream in the value chain (GHG Protocol, 2019).

Using CDP reporting, Scope 1 and Scope 2 can be identified at National level (i.e. Scotland), whereas Scope 3 is not disclosed by region, and reflects company level data.

2.2. Semi-formal interviews

Semi-structured interviews were conducted with interviewees falling into 3 categories: academia, industry and NGOs. These 3 categories offered a well-rounded representation of different views on aquaculture and gave an insight into different stakeholders' preferred carbon emissions mitigation strategies, allowing for a better understanding of aquaculture operations. In total, 11 individuals were interviewed; five from industry, 3 from academia and 3 from NGOs. The industries included aquaculture and feed companies, with participants being director, manager (or specialist positions) or certifiers. Researchers from academia interviewed had all worked on salmon aquaculture and used life-cycle assessments extensively. Participants from NGOs were either directly working on salmon species or on salmon farming.

A set of key questions were used to frame interviews and were open to allow for personalised answers or arising unplanned questions (see Supplementary Materials). Interview data was analysed using Nvivo software, where responses were coded to 6 different themes: emissions, aquaculture practices, mitigation actions, Scottish context, sustainability of salmon, and trade-offs. This thematic organisation allowed for analysis of the key recurring topics.

3. Results

3.1. CDP case studies: Mowi ASA and Grieg Seafood ASA

3.1.1. Scope 1 emissions

The results from both these large aquaculture operators indicate that Scope 1 emissions in the UK are higher than in other regions of the world, despite production being consistently lower.

Mowi's total Scope 1 emissions were 121,733 t (t) CO_2e with UK operations (predominantly Scotland) accounting for 32,657.4 tCO_2e in 2018. This is the highest emission out of the 10 locations listed in the company's annual report, despite UK salmon production only being the fourth largest operation (Supplementary Materials, Mowi, 2019). This represents 36.4% of total Scope 1 emissions for Mowi's total salmon aquaculture operations, even though total production from the UK only represents 10.2%.

GSF's Scope 1 emissions were 29,811 tCO_2e. Of these Scope 1 emissions by GSF, the Shetland site (9813 tCO_2e) was the highest emitter of all the farms (see Supplementary Materials). The Shetland Islands operations contribute 32.9% of Scope 1 emissions of GSF total salmon aquaculture operations, even though the production from the UK represents 15.9%.

3.1.2. Scope 2 emissions

Scope 2 emissions can be accounted for in two ways: location-based, and market-based. The location-based method represents the emissions calculated using the grid intensity at the location of the operations. The market-based method represents the emissions calculated from energy that the company has specifically chosen and purchased, including renewable energy credits and other energy contracts (World Resources Institute, 2015). These two methods are not complementary, meaning the resulting numbers cannot be combined.

Mowi Scotland consumed 19,513.7 MWh of electricity. This is low compared to its Norwegian operations which consumed 135,842.3 MWh. The Scope 2 emissions resulting from this consumption were 6771.3 tCO2e for location-based emissions, and 7161.5 tCO2e for market-based emissions (Supplementary Materials).

GSF consumed 7898 MWh of electricity, higher than its Canadian consumption at 5183 MWh, but lower than its Norwegian consumption at 19,562 MWh. The Shetland operations had the highest location-based emissions, at 2740 tCO_2e, and average ranking market-based emissions at 2899 tCO_2e compared to the other locations (see Supplementary Materials).

3.1.3. Scope 3 emissions

Scope 3 emissions have a larger contribution to GHG than Scope 1 or 2 (see Supplementary Materials for all Scopes). Scope 3 emissions for Mowi ASA were 1,891,612 tCO2e, representing 90% of its total emissions (2,103,006 tCO_2e) (Fig. 2). Of this amount, 1,582,202 t are from the raw materials in Mowi's own fish feed production, the emissions from feed provided by other suppliers and the transport of the fish feed to the production sites, representing 84% of Scope 3 emissions and 75% of all Mowi emissions in 2018. Other emissions in the total Scope 3 number include waste disposal and business trips taken by Mowi employees. The distribution of the final salmon product to consumers (255,611tCO_2e) represents 13% of Mowi's Scope 3 emissions, and 12% of all emissions (Figs. 3 and 4).

Scope 3 emissions for GSF were 265,301 tCO_2e, representing 89% of total emissions (299,515 tCO2e). Of this amount, 181,783 tCO_2e are due to fish feed, which is 69% of Scope 3 emissions and 61% of all emissions in 2018. The second largest Scope 3 emissions (75,082 tCO_2e) is from downstream transportation and distribution, either by air or road, representing 28% of Scope 3 emissions and 25% of all emissions, a much higher percentage than Mowi's. Airfreight is the largest contributor, and GSF discloses that air continental freight contributes 1.03 kg CO_2e/tkm (tonne kilometre). Intercontinental freight contributes 0.65 kgCO_2e/tkm, and trucking contributes 0.08 kgCO_2e/tkm.

3.2. Interview responses

With regard to 'sustainability', opinions varied between different participant categories, but were similar within categories (Table 1). In academia, the participants queried the openness of the question and sought to clarify how sustainability was defined. From industry, the question was rarely answered in yes or no terms, and participants brought up different themes in relation to sustainability. In the NGO category, all participants stated that existing Scottish salmon aquaculture was unsustainable.

With regards to GHG emissions, academics highlighted the issue of feed, agreeing that aquaculture owed over 90% of its GHG emissions to feed (Scope 3). In industry, it was clear that feed companies were aware of the emissions and were looking to reduce the impacts of their raw materials. Distribution was also mentioned as having high emissions, especially airfreight. In the NGO category, emissions were predominantly mentioned in reference to transport.

With regard to mitigation, many different strategies were mentioned by academics; some directly reducing GHG emissions, others leading to better fish health, and indirectly reducing emissions per kg of fish raised as resource efficiency is improved. The industry category presented various solutions such as novel ingredients and other innovations. In contrast to other categories, when asked what operators could do to improve their practices, NGOs pushed for a shift of farming from open-net pens into closed-containment systems, which use a physical barrier to isolate the farmed fish from the wider environment (Ayer and Tyedmers, 2009).

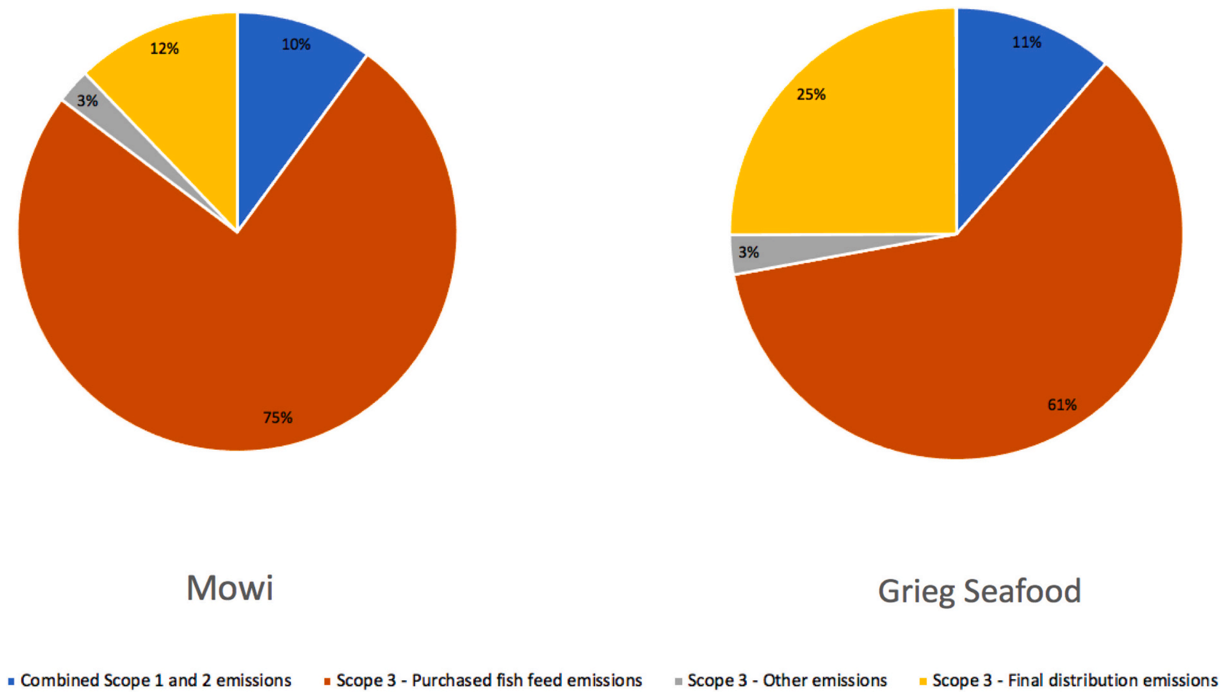

Fig. 2. Percentage breakdown of Mowi's and Grieg's Seafood emissions (right) as Scope 1, 2 and 3.

A recurring theme was trade-offs. Academics emphasised this, stating that reducing GHG emissions was not straightforward because of the interplay of different issues. Within industry, mitigation actions linked to feed repeatedly involved trade-offs too. The NGO category rarely mentioned trade-offs.

3.3. The aquaculture process

The data gathered from the literature review and the interviews demonstrates that the process starts in Scotland where the smolts are grown in hatcheries, with energy used to maintain a specific environment (temperature, water filtration, etc.) corresponding to Scope 2 emissions. When the smolts have attained the desired size, they are transported via diesel-fuelled well-boats to the ocean net pens (Scope 1). The net pens have support vessels and a feed barge, which blows the feed into the water, or powers the pen lighting. These are powered by a diesel generator (Scope 1). Once the salmon reach harvest size, they are transported via well-boats to harvest stations (Scope 1), where they are processed, chilled and packed. These stations are powered by energy that is purchased by the companies, (Scope 2). Then, the fish are distributed either to Scotland, Europe, the US or East Asia, (Scope 3). This process and its associated emissions are summarised in Fig. 3.

The largest share of Scope 3 emissions and absolute emissions in general can be attributed to the feed, the most GHG-intensive step of the salmon farming process. The feed is composed of marine ingredients and vegetable ingredients, as well as other additives such as micronutrients and astaxanthin. The marine ingredients are fishmeal (FM) and fish oil (FO), derived from processed forage fish or by-products from other fisheries, which are then transported to the feed factories. The vegetable ingredients are farmed around the world, then transported to the feed mills. These raw materials are processed and mixed, before being shipped to salmon producer countries. All these processes represent Scope 3 emissions for the aquaculture companies. However, raw materials' emissions are also Scope 3 emissions for the feed company, highlighting the global nature of the aquaculture supply chain.

4. Discussion

4.1. The global impacts of aquaculture

Previous research makes clear that salmon aquaculture emits less CO_2 than many other animal protein production processes, especially terrestrial ones. For example, Ellingsen et al. (2009) demonstrated that a salmon farmed in the UK has a CEF of 3.6 kg CO_2e/kg, in contrast to the 44.8 kg of CO_2e/kg of beef fillet at the retailer. However, this may increase if land-use change associated with feed is included (5.8 CO_2e/kg of live-weight salmon at slaughter) (Winther et al., 2020), which includes pigments to colour the salmon flesh. The efficiency of salmon can be attributed to its lower feed conversion ratio (FCR), which is a measurement of the weight of feed given to an animal divided by weight gain over its lifetime (Fry et al., 2018). If fed 100 kg in dry feeds, a yield of 65 kg of salmon fillets can be achieved, compared to 20 kg of chicken fillets and 12 kg of pork fillets (Torrissen et al., 2011). Previous work identified that the feed can represent 75–83% of GHG impacts of salmon aquaculture (Winther et al., 2020). This study was a cradle-to-gate analysis, meaning it only considered the impacts of what was used within the lifecycle of the salmon on the farm, excluding final distribution. In Scotland, feed may account for over 80% of all the impacts studied, reflecting the high GHG intensity of feeds (Newton and Little, 2018).

CDP's public data highlights the carbon imbalances in salmon aquaculture operations and its associated value chain. With regard to Scope 1 emissions, CDP data illustrates that Scottish salmon farms are high compared to other countries. Both Mowi Scotland and GSF Shetland contribute more than a third of Scope 1 emissions associated with their parent companies' entire farming operations, despite only producing 10.2% and 15.9% of their salmon output respectively. There are multiple reasons behind this; the most plausible being scale effects. Until recently, Scottish farms were capped at 2500 t of biomass with typical pens having a circumference of 80 to 120 m, compared to Norwegian ones that are up to 200 m (Berrill, 2020). Since each farm has a feed barge and support vessels, smaller Scottish farms have similar Scope 1 emissions to larger foreign farms. As a result, CO_2e/kg of salmon is higher (Cumming, 2020).

Large farms typically have quicker paybacks on new investments

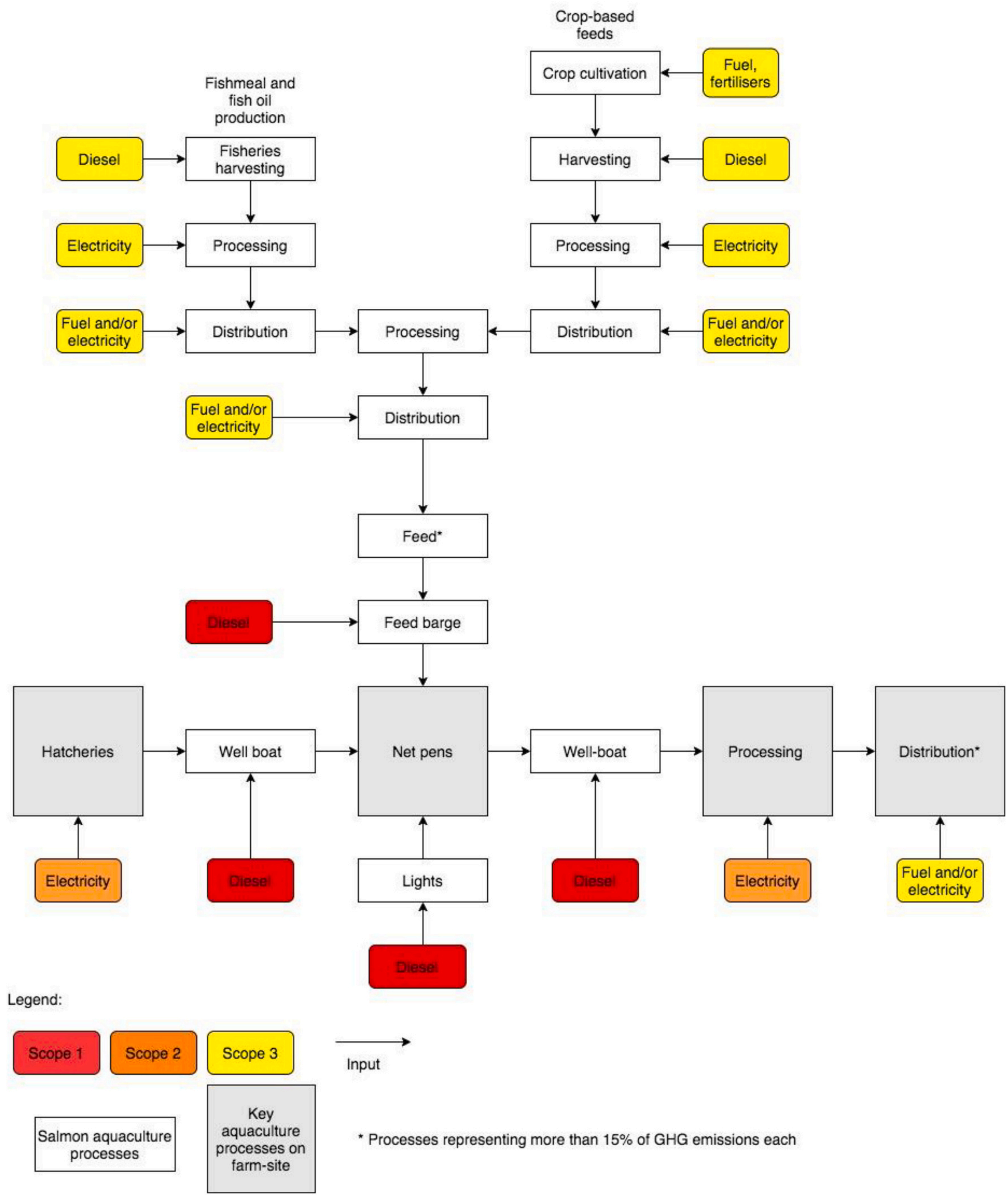

Fig. 3. Schematic of the processes involved in Salmon aquaculture and the associated emission type.

because of larger yields, meaning that investment into new equipment from companies typically goes to larger farms (Cumming, 2020). The UK has lower production in smaller farms compared to other regions in the world, and this might explain why more efficient technologies may not reach them first, leading to larger emissions than larger farms which have been retrofitted with newer equipment. Other reasons why Scottish farms contribute to higher GHG emission, include the increased vulnerability of large numbers of smaller sites to sea lice outbreaks compared to the Norwegian model of fewer larger sites (Cumming, 2020). As chemotherapeutants may be ineffective in controlling sea-lice, repeated treatments involving the use of well-boats drives up Scope 1 emissions. Other treatment methods, such as the use of warm water for physical removal of lice can also be highly energy-intensive (Cumming, 2020).

For Scope 2 emissions, Scotland has less intense emissions than Norway, although GSF Shetland has high location-based CO_2 emissions as the Shetland Islands are not connected to the UK mainland electricity grid, and are reliant on Lerwick Power Station, a diesel-powered plant.

Evidence from CDP data and the interviews point to Scope 3 emissions being the most challenging to resolve, especially those generated by feed production. This reflects the findings in the studies by Pelletier et al. (2009), Torrissen et al. (2011), and Ziegler et al. (2021). 75% of all Mowi's GHG emissions are linked to feed, and this percentage is 14% lower for GSF at 61%. Mowi's numbers match with the lower boundary found in the literature, which ranges from 75% (Winther et al., 2020) to 94% (Pelletier et al., 2009), whilst GSF does not. Distribution can help explain this disparity: most studies do not account for distribution since it takes place beyond the farm gate, with the exception of Winther et al.

Table 1
Interview responses with regard to Sustainability, GHG Emissions, Mitigation and Trade-offs. Green cells indicate all participants agreed on an answer, yellow that there was partial agreement, and red that there was no agreement.

	Main comments	Respondent Category
Sustainability	The word sustainability is too ambiguous. Salmon aquaculture itself is not sustainable, but it is more sustainable than some other farmed proteins. Answer cannot be definite.	Academia
Sustainability	Salmon aquaculture is sustainable compared to the past and in a global context (e.g. food security). Answer cannot be reduced to a 'yes' or 'no' answer.	Industry
Sustainability	Completely unsustainable: local pollution, disease and sea lice, sourcing of feed.	NGO
GHG emissions	Feed represents 90% of GHG emissions (Scope 3).	Academia
GHG emissions	Higher emissions of feed attributed to the fisheries derived part of the feed. Disagreement as one academic mentioned crop were the most emissions-intensive (this refers to different ways of accounting for emissions).	Academia
GHG emissions	Feed represents the majority of GHG emissions. Feed companies show that 60-90% of the emissions are due to agriculture of raw materials. Distribution is also an issue.	Industry
GHG emissions	Transport is an issue for emissions. The processing of fish stocks for feed as well as final transportation are all problematic. Social consequences associated with fish feed also matter.	NGO
Mitigation	Scope 3 are the most important source to tackle (Feed distribution). All feed companies need to formulate feeds with lower carbon emissions footprint (CEF) by incorporating emissions information of raw materials into feed algorithms. Reducing mortality is also key because it reduces FCR: a 0.1 increase of the FCR in fish meant an increase of 10% of feed use.	Academia
Mitigation	Many different solutions suggested: novel ingredients (algal oils, bacterial protein) for feed, setting of emissions targets for aquaculture companies, participation in Energy Savings Opportunity Scheme (ESOS) in the UK.	Industry
Mitigation	Need for more discussion and cooperation in the supply chain (e.g., asking existing suppliers to reduce emissions).	Industry
Mitigation	Closed-containment systems.	NGOs
Trade offs	Substitution of marine ingredients can lead to higher emissions from the crops that replace them, and from the micronutrients and supplements that need to be added.	Academia
Trade offs	Closed-containment systems reduce local pollution but increase Scope 2 emissions.	Academia
Trade offs	Sourcing local feed can mean higher emissions (because fisheries is more resource intensive). Reducing marine ingredients can have a detrimental effect on fish health and inefficiencies. Novel ingredients do not have sufficient data backing.	Industry
Trade offs	Closed-containment systems are much more resource intensive. Raising salmon for the entirety of their lifetime in such systems is not straightforward.	Industry
	Feeds without fish meal (FM) or fish oil (FO) can have detrimental effect on the final product.	NGOs

(2020) and Ziegler et al. (2021), who used calculations measuring the GHG emissions from different transportation methods in distribution. Final transportation of the salmon product to the consumer can contribute to substantial emissions; Scope 3 emissions from transport accounts for 25.1% of total emissions for GSF, a very high percentage, and 12% for Mowi. As such, it can be assumed that GSF has a lower percentage of emissions associated with feed compared to previous studies as emissions attributed to transport are significant.

Tackling feed production is a complex issue as it involves numerous ingredients. Increased use of forage fish for FM and FO affects the marine ecosystem and wild fisheries, and increased use of vegetable proteins (such as soy protein concentrates) affects Land Use Change (LUC). This demonstrates that whilst aquaculture is predominantly seen as an aquatic activity, wider marine and land-use impacts (such as crop cultivation) must be included as part of the value chain. In its 2018 annual reports, Mowi shows that its feed is made up of 23.5% marine ingredients (13.2% FM and 10.3% FO), and its largest vegetable contributions are from various vegetable oils (21.9%), wheat (17.1%) and soy proteins (12.1%). GSF shows that its feed is made up of 26% of marine ingredients (15% FM and 11% FO), with its main vegetable contributions being rapeseed oil (24%), wheat (20%) and soy (12.5%) (GSF, 2019; Mowi, 2019). With so many ingredients in the mix, any reduction of FM and FO could lead to substitution by vegetable proteins, essentially replacing fisheries depletion with LUC.

4.2. Evaluation of current mitigation activities

Scope 1 and 2 emissions reduction initiatives in both case studies revolve mainly around setting targets as a roadmap, with various energy efficiency and GHG reduction initiatives to achieve such targets. Mowi has set up targets to reduce Scope 1, 2 and 3 emissions by 35% by 2030 and 72% by 2050, and GSF has a target to reduce 30% GHG emissions per kg of salmon produced by 2030 with 2017 as its baseline year. Priority goals include the replacement of diesel generators by shore energy supply, and where this is not possible, with hybrid generators. GSF indicates that switching from diesel generators to grid energy in Finnmark and installing wind turbines and solar panels in Rogaland resulted in a decrease of 1119 tCO_2e, a 4% decrease of emissions from 2017 to 2018. Overall, plans for Scope 1 mitigation seem proportionate to the scale of the problem; direct use of diesel is one of the main sources of emissions on farms, and initiatives seek to target diesel generators as well as modernising equipment.

With Scope 2, initiatives should focus on reducing consumption overall: LED replacement and other Energy Savings Opportunities Schemes (ESOS) are a potentially significant means of reducing consumption. By replacing all lighting with LEDs, Mowi reduced 733 tCO_2e/year at their Belgian factory. However, such actions have less significance if the grid from which the sites source electricity continues to be fossil-fuel dependent. As such, conversion to low carbon electricity needs to be initiated. GSF Shetland's ambition to make full use of the UK grid once it is connected to the Shetland Islands (rather than remaining dependent on the Lerwick diesel plant) should lead to a reduction in emissions. Scope 2 reduction plans appear adequate in terms of on-farm reduction, but there is scope to further reduce these emissions with responsible electricity sourcing from the grid.

Scope 3 reduction plans revolve around setting targets, seeking certification, increasing engagement in the supply chain for supplier accountability, and better fish welfare. Mowi has set targets for its sustainability strategy, "Leading the Blue Revolution", with the ambition of achieving 100% traceability of raw materials, 100% certification of marine ingredients, 100% Proterra certified soy (or other equivalent schemes), as well as improved FCR and lower CEF of its raw materials. It has also set a welfare target of 99.5% survival in the sea by 2022 (Mowi, 2020a). GSF currently tackles its Scope 3 emissions by participating in an industry-led scheme funding farmers 2 USD/t of soy in Brazil to help them protect native vegetation on their land, alongside other actions such as ensuring its soy is certified deforestation-free (GSF, 2020b). It has also disclosed that it pays more for fish feed that help improve FCR. Engagement with suppliers is also key, and it asks all suppliers for environmental data to calculate the emissions from fish feed. In its CDP response, GSF clarifies that since 2015, feeds low in FM and FO have been chosen, reducing the total feeds' CEF. Like Mowi, GSF also has a sustainability programme, 'GSF 2020 Program for Sustainable Growth'. These mitigation actions will directly influence Scope 3 emissions. Tackling feed production only solves part of the issue, as fish health and welfare also impact upon emissions due to their link to feed amount. Scottish salmon farms have a non-negligible level of fish mortality, with some Mowi farms having a cumulative mortality totalling 25.5% over full production cycle, (e.g. its Isle of Rùm site (Scottish Salmon Producer's Organisation, 2020)). Failing to improve mortality levels will also lead to higher emissions from feed due to resource inefficiency (Aunsmo et al., 2010). Mortality has many drivers, but sea lice infection and disease are important issues that will only be exacerbated with climate change (Sandvik et al., 2021). Tackling fish health and welfare in general is therefore as important as tackling feed emissions.

Current efforts to mitigate these issues do not match the scale of emissions. For example, fully tackling distribution emissions would necessitate operators ceasing to airfreight their products and only shipping their salmon once frozen. Interviewees stated that freezing technology was good enough for the taste of the frozen product to be indifferentiable to the fresh product in blind taste tests. However, this scenario is unlikely in the near future due to the reluctance of companies, even though CO_2 emissions from shipping salmon are a third lower than airfreighted salmon (Ziegler et al., 2021).

Feed companies are well placed to make changes in feed production where carbon emissions are a key concern. They are undertaking many innovations and GHG mitigation activities, including developing novel ingredients to replace key Omega-3 sources such as FM and FO. Algal oil is an example: one participant stated that this could lead to formulating feeds in the future without any FM and FO if this innovation could be scaled-up. This would also reduce the emissions associated with harvesting wild fisheries and reduce the use of ingredients which can be consumed directly by human populations. Other novel ingredients include bacterial oil and insect meal. These fit better in the circular economy, as insects such as soldier fly larvae can be grown from food waste. Feed companies have established emission reduction targets and are also all pursuing sustainability certifications in their ingredients. From the participants side, they cited that much of their FM and FO is IFFO certified (IFFO is an international body that represents the marine ingredients industry and certifies fisheries designated for FM and FO (IFFO, 2020), highlighting the importance of this. One study participant stated that the soy it sourced was certified to be deforestation-free. However, the efforts by feed companies do not yet match the scale of the problems: formulation algorithms are still prioritising low cost rather than addressing carbon emissions. Innovations such as novel ingredients are not yet scaled up, so it is not possible to predict their contribution to emissions reductions. One participant mentioned that innovative ingredients usually have a CEF similar to agricultural crops, a statement echoed by the Feedback research organisation in their report which outlined that algal oil, whilst effective at reducing pressure on fisheries, increases the global warming potential of salmon by 38% compared to the use of FM and FO (Feedback, 2020). Certification, although necessary, does not always guarantee lower CEF.

4.3. Challenges and barriers to mitigation

Although companies can improve on emission reduction, efforts to do so are fraught with challenges stemming from legislation and trade-offs. Tackling feed involves many trade-offs as highlighted throughout the interviews. Reducing FM and FO, as advocated by many NGOs, would help reduce the pressure on forage fish stocks, but could lead to increased substitution of vegetable oils and proteins that could result in increased LUC as well as increased emissions from novel ingredients. Furthermore, substituting FM and FO can lead to decreased fish health as salmon's natural diet is rich in protein since salmonids feed on oil-rich plankton, copepods and small fish (SAMS, 2018). Substitution which fail to maintain this high protein, low fibre and carbohydrate diet, can impact fish health negatively. This leads to fish with higher CEF, despite the feed used being lower in carbon. One participant stated that it was almost impossible to have feeds that have no marine ingredients and still be low-carbon.

A trade-off which could be important in the future involves closed-containment technologies. Whilst beneficial in regard to limiting adverse impacts of aquaculture such as sea lice infections, accumulation of fish faeces under the pens and eutrophying emissions, closed-containment technologies inevitably consume more energy than open cage pens. While closed-containment could predominantly help to limit local emissions into the marine environment, they release higher amounts of emissions, shifting a local problem into a global one (McGrath et al., 2015). One industry participant explained that in Norway, the industry had ambitions to multiply its current production by 5 by 2050. Key considerations for using such technologies are the type of closed-containment systems, and the location for a greener electricity grid. However, recent research indicates that use of recirculating aquaculture systems (RAS) would not increase GHG emissions disproportionately; Bergman et al. (2020) evaluated the impacts of tilapia farmed commercially in Sweden in RAS systems, and noted that the biggest contributor to GHG emissions remained feed. This is the case despite higher energy use attributed to the grow-out phase (Bergman et al., 2020). Furthermore, GHG emissions would only increase if the energy used by closed-containment systems is non-renewable, something which is less of an issue in Scotland. Going forward, this is something that the Scottish Government has to consider when expanding the Scottish aquaculture industry given its net zero commitment by 2045. Locating farms close to market, as some participants from the NGO category have suggested, would also result in a reduction in the impacts of the final distribution of the product as an added benefit.

Legislation is a significant challenge in Scotland when it comes to aquaculture, which can be linked indirectly to the inefficiencies which contribute to higher carbon emissions. One participant heavily criticised the legislation, showing that it was a driver in contributing to Scope 1 emissions due to restriction of scale. The legislation is described as "fractured and inefficient" (Participant 10), due to the multiple licenses needed from different regulating bodies, and the difficulty in implementing changes on farms. Whilst this itself is not directly correlated to issues in GHG emissions, a more efficient licencing system could allow for more focus on key issues such as mortality and GHG emissions, which are not currently considerations. A participant from the industry mentioned that to "overhaul the legislation" would be the most efficient way of creating change and starting to use a more holistic way of looking at aquaculture, integrating energy use and GHG emissions alongside issues such as seabed impacts.

A key problem slowing down rapid change in the supply chain is market incentives. As of now, feed companies formulate based on lowest prices mainly because there are no incentives to do otherwise. Aquaculture operators also expect to have low-priced feeds. As such, substituting ingredients based on CEF would lead to higher prices, dissuading operators who would then look for other suppliers. One participant mentioned that for feed companies to truly incorporate the solutions needed at the appropriate scale, the market had to value the changes implemented (sustained demand despite high prices). Realistic ways this could be achieved could include subsidies or marketing for more premium, low carbon salmon, prompting consumers to choose a more responsibly farmed salmon above the low-priced ones. Unless this happens, mitigation might not match the scale needed for systemic and meaningful change. Another key issue which hinders large scale change is the difference in priorities for all the stakeholders involved in aquaculture as highlighted by the difference in opinions from the participants. When it comes to the most important strategy to reduce carbon emissions, all categories had different points of view. Academics emphasised the use of information for meaningful change through the incorporation of low carbon information in feed formulation or precision aquaculture for increased fish welfare. Industry answers were more varied, but revolved around innovations, fish health and more cooperation throughout the value chain. NGO answers were focused on closed-containment technologies. This difference in opinion from the NGO category highlights that there exist many other pressing concerns outside of carbon emissions in salmon aquaculture which urgently require solving. If more discussion between different categories could be facilitated further, this could lead to converging efforts and increased effectiveness.

4.4. Recommendations towards cleaner production

This study has highlighted the different carbon emissions sources from Scottish salmon aquaculture. Particularly problematic to the industry are Scope 3 emissions, the largest source throughout the value chain and the least well targeted of the three Scopes. These findings have important implications: unless Scope 3 emissions are properly targeted and resolved, the Scottish salmon aquaculture industry will find itself penalised by upcoming climate legislation, locally and internationally. Mowi and GSF, like most international aquaculture operators, have sustainability plans. However, these clearly need to be much more ambitious, especially given Scotland's net zero emissions target for 2045. Furthermore, as international companies with a large market in the EU, Mowi and GSF will need to adhere to EU regulations, such as the upcoming EU Taxonomy. Failure to mitigate emissions may impact future investment and a stabilisation in meat demand in developed markets due to climate conscious consumers (Henchion and Zimmermann, 2021). To support future efforts, further analyses of aquaculture should build on methods here and cover all emissions from cradle to grave to assess a complete GHG footprint.

Below are a set of recommendations based on interview and CDP data above for policy stakeholders within the value chain, on what could contribute to the sustainability of Scottish salmon aquaculture.

For Policy-Makers

1. Provide funding for innovative solutions such as novel feeds.
2. Support sustainable aquaculture through legislation, for example with licencing relating to clear KPIs and standards on emissions.
3. Promote engagement between stakeholders to highlight different concerns, allowing for more transparency and communication, and potential minimisation of some trade-offs.
4. Require carbon emission data to be fully transparent to consumers, for example requiring CEF labels on salmon products. If this is to be done, mandatory standards for calculations should be set to avoid use of calculation methodology artificially decreasing CEFs.

For NGOs

1. Continue to raise awareness of environmental issues in aquaculture to support consumers in making more sustainable choices with regard to farming standards.
2. Be aware of the different trade-offs when it comes to carbon emissions mitigation.
3. Engage with aquaculture operators in dialogues towards more sustainable practices to balance mitigation with emissions.

4.5. Conclusion

From the standpoint of GHG emissions alone, salmon aquaculture is sustainable compared to many other protein production processes, but there remain numerous opportunities to reduce emissions further. Using CDP data is an innovative route to evaluate operators, and in this case their use identified imbalances driven by Scope 3 emissions. It is clear that feed production is the most GHG-intensive step in the aquaculture process, representing not only the majority of Scope 3 emissions, but of total emissions. Despite this, Scope 1 and 2 emissions should not be overlooked, especially as they are within the control of the operators and thus the easiest to reduce. The actions to reduce Scope 3 emissions are much more challenging, involving mitigations which require technological innovations, and considerable trade-offs. Without balanced mitigation strategies, the Scottish salmon aquaculture sector might find it increasingly hard to operate in a warming world and face reputation and legislative challenges. While there are a number of immediate steps that can be taken to reduce emissions modestly, this study highlights the opportunities and challenges for the industry in collaboration with Government and end users, to create a framework that would support a growing and sustainable salmon aquaculture supply chain.

Author Statement

We declare that there are no competing interests in this manuscript. Sebastian Hennige, on behalf of all co-authors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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