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RESEARCH ARTICLE

Insight into real-world complexities is required to enable effective response from the aquaculture sector to climate change

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Abstract

This study demonstrates how a comprehensive knowledge base can be used by the aquaculture industry, researchers, and policymakers as a foundation for more targeted and detailed climate change impact analysis, risk assessments and adaptation planning. Atlantic salmon (*Salmo salar*) production in Norway was used as a case study and to illustrate the need to consider impacts from multiple stressors across different production stages and the wider supply chain. Based on literature searches and industry news, a total of 45 impacts and 101 adaptation responses were identified. Almost all impacts were linked to multiple climate stressors, and many adaptation responses can be used for a range of impacts. Based on the research, a move towards more targeted and detailed assessments is recommended. This can be facilitated through a strong knowledge base, further research to address complexities, and better communication between all stakeholders. The results also demonstrate the need for more climate change research that reflects the challenges that the aquaculture sector faces, where multiple stressors and the range of impacts across production stages and the wider supply chain are included. Highlighting the wide range of stressors, impacts and adaptation responses provides a more holistic understanding of the real-world complexities that aquaculture producers face. This again could facilitate adoption of more effective responses to climate change needed to maintain or increase production sustainably.

1. Introduction

Human activities and anthropogenic greenhouse gas emissions have led to unprecedented rates of climate change [1,2]. Impacts have been reported in terrestrial, freshwater, and marine ecosystems, at all scales, from individual organisms to communities [3]. Observed changes in climate stressors include increased air and sea temperatures, rising sea level, more frequent extreme weather events, and changes in rainfall [1,2]. Continued emissions will result in further atmospheric and oceanic warming, with long-term changes to the climate system, which will exacerbate existing risks and create new challenges for all life on earth [1].

data collection and analysis, decision to publish, or preparation of the manuscript.

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Climate change is already affecting food production worldwide, including aquaculture [4]. For example, studies have shown that sea level rise and saltwater intrusion, amongst other climate stressors, are affecting production of prawns in Bangladesh [5] and extreme weather events have damaged ponds in the Czech Republic, leading to loss of fish [6]. Industry news articles state that a heatwave decimated mussel production in Greece [7] and multiple stressors, including high temperatures and low oxygen levels, have contributed to salmon mortality events in Canada [8]. These wide ranging cases are only a small indication of some of the effects of climate change on aquaculture production. Since aquaculture includes a diversity of production systems, species, and farming environments [9], assessment of climate change effects is complex as impacts will vary considerably, as will the ability to adapt and respond. As in other sectors [10], it is often local-scale issues that are most relevant to individuals, businesses, or communities, and these are not captured in high-level or generalised assessments. Production at an aquaculture site is influenced by many different climate, biological, and environmental factors that vary spatially and temporally [11–13], and even sites that are relatively close together can have very different conditions and farm practices. If the aquaculture industry and associated stakeholders are to prepare effectively for future challenges from climate change, then there is a need to consider how individual species are produced, the scale at which decisions are made, where impacts would occur, and how adaptation responses can be implemented.

Evidently, given the nature of aquaculture production, it is important that companies identify and analyse how their operations may be affected by climate change to ensure responsible and sustainable production [14,15]. Thus, many companies and aquaculture organisations are interested in doing their own climate change assessments, and some countries are making climate risk reports mandatory for large companies and institutions [16]. The Task Force on Climate Related Financial Disclosures (TCFD), set up by the Financial Stability Board (FSB), an international body that coordinates efforts to support and strengthen the global finance system, provided a set of recommendations on making climate-related financial disclosures about exposure to climate risks [17]. It is likely that this is the start of such reporting becoming common practice in business, especially if these are required to secure investments or insurance [18].

In preparing climate change risk assessments and future strategies, companies must evaluate how their operations will be exposed to climate stressors and potential imapcts they may have. Multiple stressors, how they interact, and their individual and combined effects, is recognised as an area that needs attention to maintain or increase aquaculture production under climate change [12,14,15,19]. Aquaculture is further complicated as there are usually multiple stages to production, the different life stages of the farmed species each have specific biological requirements, different production technologies are used, and the farms are located in a range of varying environmental conditions [20]. Beyond the farm level production stages, there is also a wider supply chain that provides key inputs and ensures the product makes it to market. The wider supply chain also has species and area specific challenges [21,22]. All of these factors are the reality for the aquaculture industry, making development of climate change risk assessments highly complex and difficult.

The aquaculture industry and associated stakeholders can also consider a range of adaptation responses that are available, or could be developed, such as new technology and selective breeding, to alleviate some impacts and risks [14]. However, adaptation is also complicated, as one adaptation response may directly or indirectly affect another, and some responses may be effective in the short-term, but could have long-term, often unintended, consequences [23,24]. It is also possible that some adaptation responses could lead to maladaptation, with negative effects greater than the risks the original response was intending to alleviate [25]. Thus, effective adaptation requires an oversight of the range of climate stressors, impacts, and possible adaptation responses to ensure future strategies are appropriate.

Clearly, there are many things that should be considered within climate change impact analysis and risk assessments for aquaculture. Studies in other sectors have shown that collating and synthesising existing knowledge can be a useful way to identify relationships between different factors [26,27]. Reviews of existing knowledge also allow identification and prioritisation of knowledge gaps and emerging research needs [28]. Given the diversity of aquaculture [9], it is important to recognise that information for one species may not be directly relevant for another, likewise, not all locations and production systems will be exposed to the same challenges from climate stressors [29]. Targeted area and species-specific knowledge bases would be a way of visualising and describing links between climate stressors and impacts, allowing individuals and organisations to extract relevant information to perform their own assessments using their case-specific information.

The overall aim of this study was to gain insight into the real-world complexities of aquaculture and climate change, and the level of detail required for assessment, by compiling information for a specific species and area. Norwegian Atlantic salmon (*Salmo salar*) production was used as a case study. Salmon is a cultured aquatic species of high commercial importance, and Norway represents over half of all production [30]. First, the scope and boundaries were set by defining the relevant production stages and wider supply chain components, as well as the climate stressors they are exposed to. Second, 'Documented links' and 'Potential links' between climate stressors and impacts were identified. Third, possible adaptation responses were outlined. Finally, the information was compiled within an Excel workbook (S1 Appendix).

2. Methodology

The research draws on an earlier risk assessment conducted for wild capture seafood by Seafish [31] as part of the wider climate change adaptation framework in the United Kingdom [32]. However, the purpose of the present study was not to undertake a risk assessment or establish risk scores, hence the report prepared by Seafish rather provided a basis for how to present complex information on multiple climate stressors, impacts, and adaptation responses. In this study, the focus was on a stock-take of existing information, from published literature and news articles, to identify links between climate stressors and impacts, as well as potential adaptation responses. This was a three-stage process: 1) Establish the scope and identify system boundaries, 2) Determine links between climate stressors and impacts, and 3) Identify adaptation responses. Further information on each of these stages is provided in the following subsections.

2.1 Scope and identification of system boundaries and climate stressors

Norwegian aquaculture is dependent on multiple farming stages, resource inputs, support networks, and extends across the entire coastline (Fig 1). Thus, it was necessary to consider the different production stages, including salmon biology at the different developmental stages, and key parts of the wider supply chain. The assessment was based on present-day practices (2015–2020).

2.1.1. Salmon production in Norway. To meet the physiological requirements of Atlantic salmon throughout each life stage, aquaculture producers use different production systems and environments. Broodstock fish are usually held in land-based facilities, or in sea cages until they are ready to spawn, when they are then moved to tanks in land-based facilities. Eggs are fertilised and hatched in indoor, freshwater hatching trays [20,33]. At first feeding, fish are transferred to larger tanks [34], with either flow-through or recirculated (RAS) freshwater,

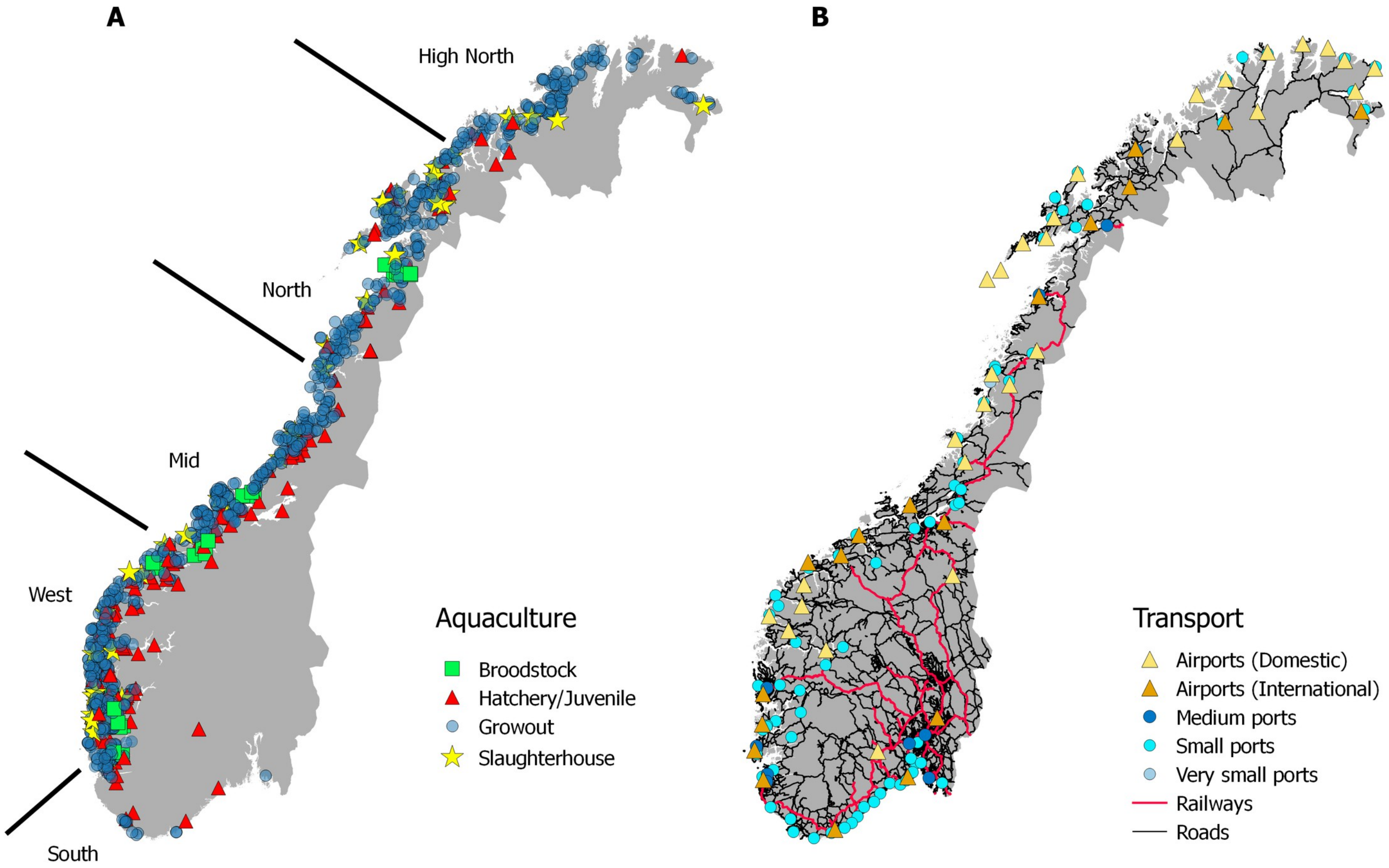

Fig 1. A) Map of salmon aquaculture production facilities in Norway, using data extracted from The Norwegian Directorate of Fisheries (https://kart.fiskeridir.no/) B) Map of key features of the transport network in Norway. Road and Railway data sourced from OpenStreetMap via Mapcruzin. Airport data based on annual statistical data for 2019 from Avinor (https://avinor.no/en/corporate/about-us/statistics/archive); International airports were categorised as those airports with at least one scheduled international operation. Data on ports was obtained from World Port Source (www.worldportsource.com), and their size classification (small, medium) is used here.

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which may be within the hatchery or another juvenile production facility. The fish are generally kept in the juvenile production systems until they undergo smoltification, which is the physiological process by which salmon adapt from freshwater to seawater. Once ready for the sea, salmon are transferred from the freshwater facility to sea-based cages where they remain until harvest, around 15 months, depending on location and desired harvest size. After harvest, live salmon are transported from cages to the slaughterhouse by wellboats, where they are stunned, slaughtered, processed, and packed, before being transported to a secondary processing facility or onwards to market via road, rail, or air transport.

Climate change is (or will) affecting all aspects of life on earth in some way [3]. It is not possible to assess every single direct, indirect, and combined consequence of these changes on Norwegian salmon aquaculture, not least because there are still many unknowns and factors that are unpredictable. This assessment focused on salmon production from hatchery to harvest. The different life stages and production systems will have different exposures and vulnerabilities to climate change. Accordingly, for this study, six key stages and components of the supply chain were identified: 1) *Breeding and Hatchery*, 2) *Juvenile*, 3) *Growout*, 4) *Slaughter and processing*, 5) *Transport*, and 6) *Feed*. Fig 2 shows how these stages and components are connected.

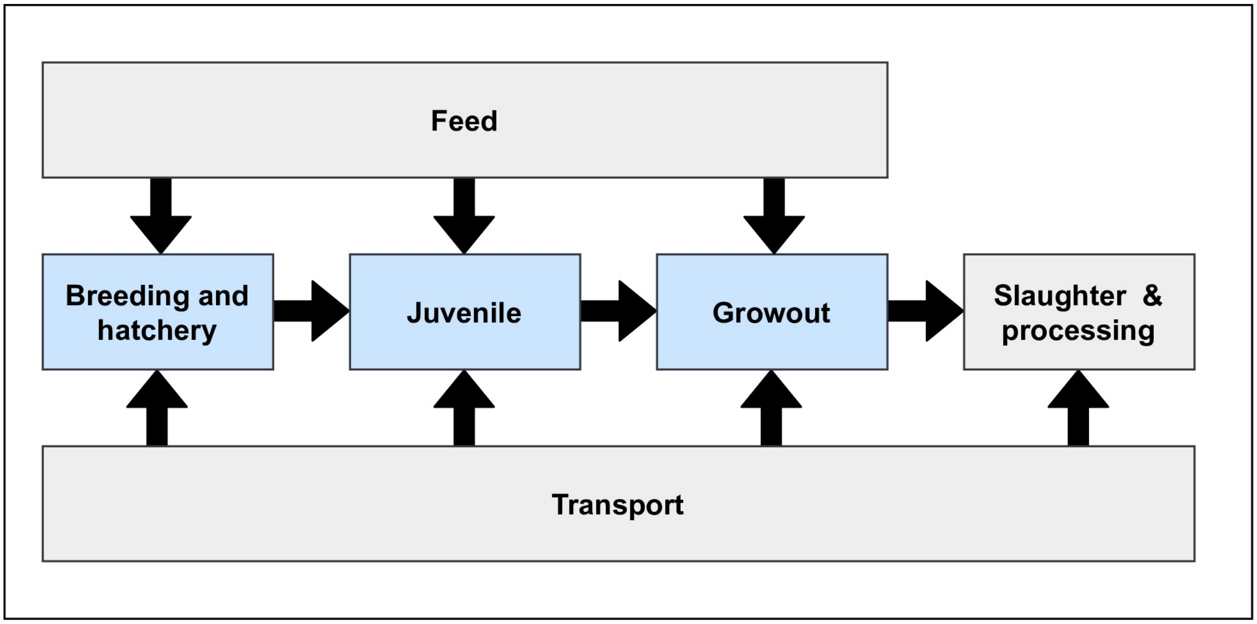

Fig 2. Overview of the different stages in production (Breeding and hatchery, Juvenile and growout) and post-production and wider supply chain (Slaughter and processing, Feed and Transport).

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2.1.2. Norwegian coastal climate and climate stressors. Norway has a long coastline, with many islands, inlets, bays, and fjords. The country extends across 13 degrees of latitude (58–71˚N), with arctic conditions in the North and temperate conditions in the South. However, it is important to note that climatic factors are spatially and temporally heterogeneous and the rate and magnitude of climate change also varies [35]. Hence location has a major influence on how aquaculture will be affected by climate change.

A range of climate factors considered to have an impact on salmon production (hereafter climate stressors) were identified and categorised as: 1) Sea level rise and extreme water levels, 2) Storms, 3) Air or sea temperature, 4) Extreme temperatures and heatwaves, 5) Ocean acidification, 6) Deoxygenation, and 7) Changes in precipitation/runoff. Scientific literature and published reports were used to provide the context on each climate stressor and how they might affect aquaculture production (Table 1). Other stressors may also have impacts but these were the main stressors identified and used in the Seafish assessment for capture fisheries [31], and more recently, aquaculture [36], and are also considered important in other documents such as the large review by the Food and Agricultural Organization of the United Nations (FAO) [4], thus the authors of the present study considered these stressors appropriate for use here.

2.2. Identification of links between stressors and impacts, and possible adaptation responses

Climate change studies often mention the following: impact, adaptation, and mitigation. Each of these terms is outlined clearly by the IPCC [2]. In brief, impact refers to the effects of climate change on natural and human systems, adaptation is the process of adjusting to existing or expected climate change and its effects, and mitigation is a human intervention to reduce greenhouse gas emissions at the source or decrease greenhouse gas concentration in atmosphere. In the present study, the focus was impact and adaptation.

Table 1. Climate stressors that are relevant to salmon aquaculture in Norway. Where numbers are given for the projected changes, they are given as median values by the end of this century from climate projections under the highest among the available scenarios (RCP8.5) in the report from the Intergovernmental Panel for Climate Change [2].

Climate Stressor	Conditions in Norway
Sea level rise and extreme water levels	Global mean sea level is rising at an accelerating pace, though there are regional differences [2]. In Norway, model projections suggest that mean sea level will increase along the entire Norwegian coastline, with regional differences due to post-glacial uplift and the highest rises expected in South and Western Norway [35,37,38]. Mean sea level rise is a slow and gradual process, however even moderate changes can increase extreme water events, potentially leading to coastal flooding, and erosion [39]. Norway is often considered to be less vulnerable to sea level rise and extreme water levels due to its characteristic steep topography [40]. But in low-lying coastal areas, storm surges have caused considerable damage to buildings and transport infrastructure in the past [41]. In the future there could be increased incidences, as model projections for Norway show an increase in storm surges and extreme water levels [35,37,38]. Regions in the high north tend to have steeper profiles, and there are more low-lying areas found in the South and West [40], thus within any region there will be local variation.
Storms	There is likely to be changes in storms, winds, and waves, however there are many uncertainties associated with the modelling process for storms, mostly due to the lack of long-term data and the scale of the models. The frequency and intensity of storms in the North Atlantic have increased since the 1970s [42]. Between 1961–2010, most of Norway experienced a slight increase in strong winds/gales (wind speeds >15m/s), but with large differences between years and areas [35]. Some model projections suggest there will be increased storm activity in the Norwegian sea, e.g. an increase in storm intensity [43], while others suggest there may be a decrease [44]. Exposure to storms will also depend on the location and physical characteristics of the environment (e.g. sheltered or exposed).
Temperature	Globally, air temperature has been increasing at an accelerating rate since the mid 1800's [1]. There are regional and seasonal differences, with some areas warming faster than others and in Norway annual mean temperature is expected to increase by 4.5°C (interval 3.3–6.4°C) by the end of the century, with the largest increases occurring in spring and winter [35]. Model projections indicate this will continue, with the largest increases expected in the North and smallest for the West [35]. Mean annual sea temperatures are also increasing [35], but the variability of conditions is more important than average temperature for most aspects of salmon production [29]. Furthermore, as the country extends over a large latitudinal range, from warmer waters in the south to colder conditions in the north, temperature increases will have different implications depending on location [29]. Temperatures in freshwater lakes and reservoirs (potential water sources for hatchery and juvenile stages) are also expected to increase, either at a similar or higher rate than air temperature trends, with lakes in higher latitudes generally warming faster than lakes in other areas [45]. Although, as with other aquatic systems, the implications of increasing temperatures in lakes will depend on physical and ecological characteristics.
Extreme temperatures and heatwaves	The IPCC are virtually certain that throughout the world there will be increases in the frequency and magnitude of warm daily temperature extremes and decreases of cold daily temperature extremes over the 21st Century [46]. A heatwave, whether in air, marine, or freshwater, is defined as temperature above a percentile threshold, and will depend on the baseline temperatures at a location. Marine heatwaves are difficult to predict, but an increase in the frequency and duration of these events over the last century have been registered [47,48]. Likewise, lake systems have been shown to undergo increased occurrence of heatwaves and these are also projected to increase in frequency as well as becoming longer and hotter, towards the end of the century [49]. The consequences of a heatwave in a particular location will vary, i.e. a marine heatwave in the colder conditions in the north of Norway has different implications for salmon than a marine heatwave in warmer conditions in the south.

(*Continued*)

Table 1. (Continued)

Climate Stressor	Conditions in Norway
Ocean acidification	Ocean acidification is taking place at an increasing rate as CO_2 is absorbed by surface waters [2], but throughout the world there are regional differences. Studies have shown the Norwegian basin undergoing faster acidification than the global mean [50]. Within Norwegian waters, there are also differences between areas and seasons [51]. Northern Norway is more vulnerable to ocean acidification due to the seawater characteristics and cold-water temperatures [51,52]. However, there are many uncertainties and knowledge gaps associated with ocean acidification, especially the rates of change in coastal regions in comparison to the open ocean [53].
Deoxygenation	Ocean oxygen levels are decreasing due to increasing ocean stratification, changing ventilation, and biogeochemistry [2,54]. In coastal areas, oxygen depletion also occurs where there are inputs of large quantities of nutrients (e.g. land runoff or sewage plants) leading to eutrophication, oxygen depleted areas or hypoxic zones [54]. A decreasing trend in oxygen concentration has also been observed in Norwegian fjords [55,56]. Deep fjords are characteristic of the Norwegian coastline and are the locations of many salmon farms. Climate change may also influence oxygen levels in freshwater environments, and increased temperature and changes in wind mixing may contribute to decreased oxygen levels in lake systems [57].
Precipitation/runoff	Changes in precipitation will vary between locations [42]. In Norway, annual precipitation is expected to increase by about 18% (interval 7 to 23%) by the end of the century, with the largest relative changes expected in the north, and the largest absolute changes in the west [35]. For areas in the north, increased temperatures will lead to a decrease in snow and increase in precipitation falling as rainfall, which will affect runoff and flood generation [58]. Rainfall and snowmelt can trigger flash floods and landslides [59]. It is expected that snowmelt floods will decrease in magnitude and frequency, but rainfall induced floods will increase [35]. Models suggest extreme precipitation events will increase in frequency and intensity [60] with severe consequences for western and southern Norway [61]. Changes in precipitation and runoff affect salinity and other water quality parameters in fjords, influencing the biogeochemistry and ecosystem processes [62]. Runoff from land contributes organic matter to coastal and fjord environments, and this varies seasonally and between locations [63]. Likewise, organic matter also enters freshwater systems via runoff, and this can affect water quality (e.g. increased turbidity). Droughts also occur in Norway, with low lake and groundwater levels occasionally affecting freshwater supplies in western and southern regions, and an increase in drought duration and drought affected areas is expected in the future [64].

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To obtain information on links between climate stressors and impacts, there was a search of scientific and grey literature via the Scopus database and Google Scholar. The literature was restricted to documents that were in English or Norwegian and no time limits were set for the searches. As this was not a quantifiable literature review or a meta-analysis, the aim was to find studies or news articles that described a link between a climate stressor and possible impact rather than identify every study that mentioned the link between the stressor and/or impact. Initial searches focused on the seven climate stressors (‘*Sea level rise and extreme water level*’, ‘*storms*’, “*temperature*’, ‘*extreme temperatures and heatwaves*’, ‘*ocean acidification*’, ‘*deoxygenation*’, ‘*rainfall/runoff*’) as well as ‘*salmon aquaculture*’, ‘*salmon farm**’, ‘*salmon production*’, ‘*salmon health*’, ‘*salmon feed*’, and similar terms from the different production stages and supply chain outlined in Section 2.1.1. For the Transport category, broader searches were used that focused on the Norwegian transportation network. Where relevant, in-text citations of literature were also consulted. Literature searches were guided by the authors personal knowledge and experience, as well as general information from industry representatives and associated stakeholders. To account for industry experience that may not be reported in scientific literature, the major industry trade magazines and websites (e.g. Intrafish, Salmon

Table 2. Rationale behind linking climate stressors to impacts.

Category	Description
Documented link	Evidence suggests or shows a link between stressor and impact based on scientific literature, grey literature, or industry news, that a climate stressor will have impact
Potential link	Limited evidence in scientific literature, grey literature, or industry news to link stressor to impact, but this could be due to lack of studies and lack of events so far
Not applicable	At present there appears to be no evidence based on scientific literature, grey literature, or industry news that a climate stressor would have impact

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Business/iLaks, The Fish Site, Fish Farmer) were searched via Google for links between climate stressors and impacts.

The information was compiled within an Excel workbook (S1 Appendix), and the link between the climate stressors and impacts were categorised by the authors as 'Not Applicable', 'Potential link' or 'Documented link', as described in Table 2. All of the authors reviewed the categories multiple times over the course of the assessment to improve consistency of categorisation across the impacts. It is important to note that the categories do not reflect the magnitude of the impact nor the likelihood or probability of an impact to occur. They only explain there is ('Documented'), or could be ('Potential'), a link between the stressor and the impact based on the available evidence. Since literature can be unbalanced [65], and a high number of studies can focus on a topic and still have large knowledge gaps and a small number of studies can consider a topic and resolve all knowledge gaps, the difference between 'Documented' and 'Potential' was largely based on interpretation of the literature by the authors. This involved reviewing the available information within studies and making a judgement on whether there was enough information to link a climate stressor to an impact. In presenting the results, a narrative approach was used to describe how the information suggested or supported a link.

Possible adaptation responses were identified and categorised based on several factors: type, setting, responsibility, timing, and resources (Table 3). These factors were considered important as they would influence decisions on which adaptation responses could, or should, be used [31]. Again, these categories were based on interpretation of literature by the authors and the categorisation was reviewed multiple times by all of the authors before the final version for consistency. The analysis focused on development of responses but did not consider the costs of implementing the adaptation response, as this will depend on several factors and is likely to vary between areas and companies.

3. Analysis

The full knowledge base, which includes further descriptions and associated references, is available in the Excel workbook in the S1 Appendix and provides detailed descriptions and references to explain the link between the stressors and impacts, as well as possible industry innovations, adaptation responses, and research needs. It must be emphasized that the lists are not exhaustive, as emerging issues and unknown impacts or adaptation responses may be missing, but they provide a wide knowledge base as a starting point for assessments.

3.1. Impacts of climate change

The following subsections provide an overview and summary of the key findings linking climate stressors to impacts for the different stages of production and the wider supply chain, as outlined in Figs 3 and 4. Overall, 45 impacts were identified across all stages, and 154 'Documented links' and 58 'Potential links' between climate stressors and impacts. The impacts are not single branches of knowledge, and instead focus on topics that have one or more

Table 3. Adaptation categories.

Category	Description
Type: *What* the adaptation measure would focus on	
Biology	Production aspects relating to physiology, health, and welfare of the fish
Environment	Environmental conditions (e.g. temperature of the production system)
Policy	Policy, plans, standards, legislation, and regulation
Technical	Technology, engineering interventions, and operational responses
Setting: *Where* the adaptation measure would be positioned	
Farm	Aquaculture site level (e.g. sea pens, tanks, buildings, wellboats)
Industry	Industry level not specific to individual aquaculture farms
External	Measures that are not specific to aquaculture
Responsible: *Who* would take the lead role in developing the adaptation response	
Industry	Aquaculture producers, feed companies, breeding companies, engineering specialists, transportation companies
Researchers	Industry research & development departments, research institutes, universities
Government	Regulators, policymakers, politicians
Other	Organisations that are not focused on aquaculture (e.g. agriculture, fisheries)
Time: *How long* it would take to develop the adaptation response	
Short	Within 5 years
Medium	5–15 years
Long	Over 15 years
Resources: *How much* research and development required for adaptation responses	
Minor	Available knowledge and resources can be used to develop adaptive responses
Moderate	Requires some additional knowledge and/or resources to develop adaptive responses
Major	Requires substantial additional knowledge and/or resources to develop adaptive responses

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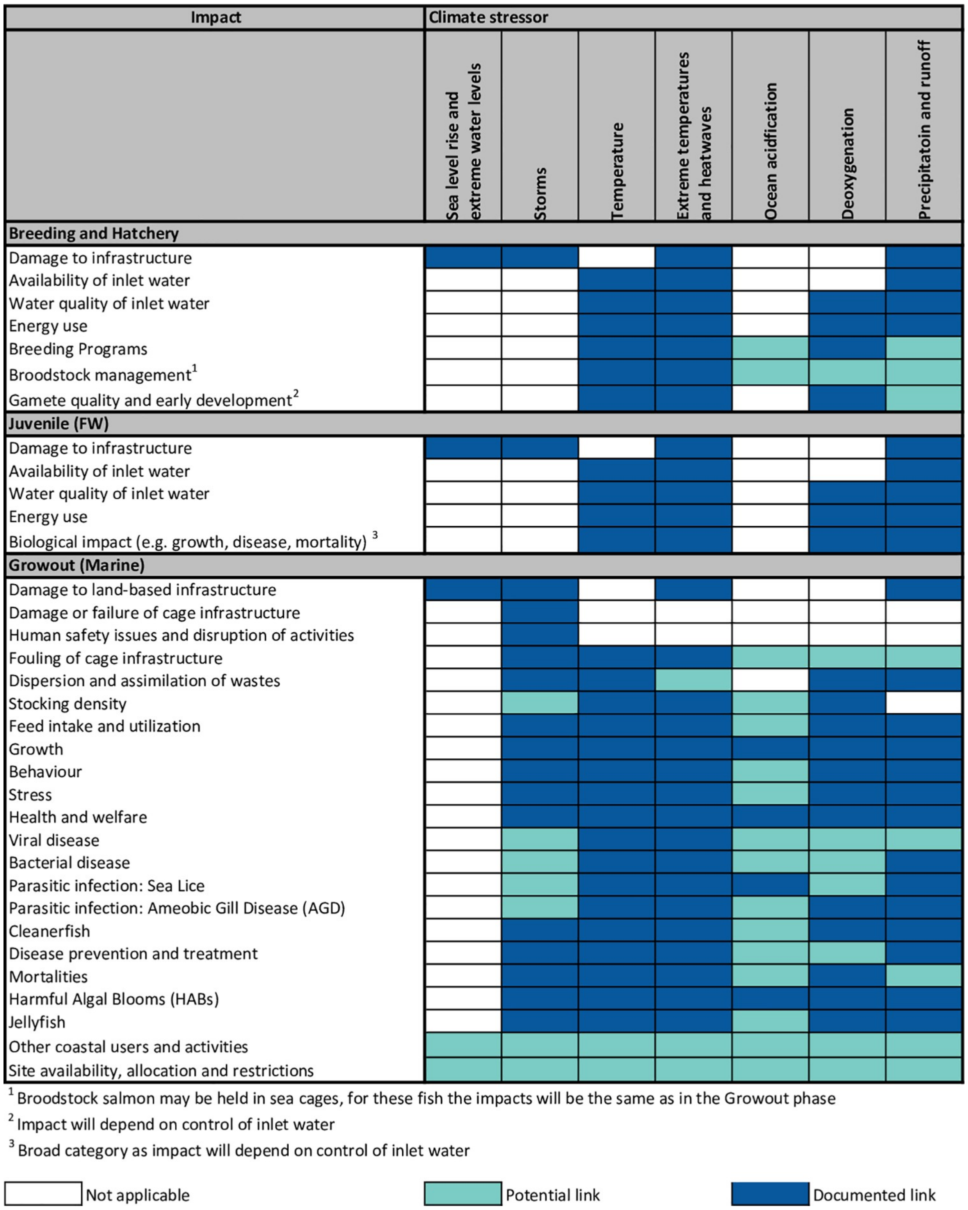
biological, environmental, technological, socio-economic, or other aspects, highlighting the need for understanding across a range of disciplines to address the real-world challenges that Norwegian salmon aquaculture faces.

Between and within stages, the impacts are not equal, and may differ in both effect and magnitude. For some climate stressors and impacts, more information was available than for others. Temperature was one of the stressors where it was easier to establish 'Documented links' with impacts due to the number of studies available and industry reports. In contrast, there were few studies on ocean acidification, and there was uncertainty about how this may affect salmon aquaculture. There were some identified impacts that were common across multiple stages, such as damage to land-based infrastructure, while others were specific to an individual stage. *Breeding and Hatchery* and *Juvenile* stages are similar due to their production environments, with operations primarily in land-based flow through or recirculating systems, so they would have a similar exposure to climate stressors.

3.1.1. Breeding and hatchery. There were 7 impacts identified within *Breeding and Hatchery* (Fig 3), all of which were linked to multiple stressors. Damage to infrastructure had 'Documented links' to 4 climate stressors (*Sea level rise and extreme water levels*, *Storms*, *Extreme temperatures and heatwaves*, *Precipitation/runoff*). Breeding and hatchery facilities are located close to the coast (Fig 1), and studies have shown that many Norwegian coastal areas are susceptible to flooding from storm surges due to sea level rise [40,41], which may cause damage to buildings and wider infrastructure. Storms are also known to cause destruction within affected areas, e.g. disruption of power supplies and damaged buildings and infrastructure [66]. Heatwaves, or sudden temperature changes, and/or precipitation can lead to avalanches, rockfalls, and landslides which can result in infrastructure damage [67,68].



Impact	Climate stressor						
	Sea level rise and extreme water levels	Storms	Temperature	Extreme temperatures and heatwaves	Ocean acidfication	Deoxygenation	Precipitatoin and runoff
Breeding and Hatchery							
Damage to infrastructure	🟦	🟦	⬜	🟦	⬜	⬜	🟦
Availability of inlet water	⬜	⬜	🟦	🟦	⬜	⬜	🟦
Water quality of inlet water	⬜	⬜	🟦	🟦	⬜	🟦	🟦
Energy use	⬜	⬜	🟦	🟦	⬜	🟦	🟦
Breeding Programs	⬜	⬜	🟦	🟦	🟩	🟦	🟩
Broodstock management[1]	⬜	⬜	🟦	🟦	🟩	🟩	🟩
Gamete quality and early development[2]	⬜	⬜	🟦	🟦	⬜	🟦	🟩
Juvenile (FW)							
Damage to infrastructure	🟦	🟦	⬜	🟦	⬜	⬜	🟦
Availability of inlet water	⬜	⬜	🟦	🟦	⬜	⬜	🟦
Water quality of inlet water	⬜	⬜	🟦	🟦	⬜	🟦	🟦
Energy use	⬜	⬜	🟦	🟦	⬜	🟦	🟦
Biological impact (e.g. growth, disease, mortality) [3]	⬜	⬜	🟦	🟦	⬜	🟦	🟦
Growout (Marine)							
Damage to land-based infrastructure	🟦	🟦	⬜	🟦	⬜	⬜	🟦
Damage or failure of cage infrastructure	⬜	🟦	⬜	⬜	⬜	⬜	⬜
Human safety issues and disruption of activities	⬜	🟦	⬜	⬜	⬜	⬜	⬜
Fouling of cage infrastructure	⬜	🟦	🟦	🟦	🟩	🟩	🟩
Dispersion and assimilation of wastes	⬜	🟦	🟦	🟩	⬜	🟦	🟦
Stocking density	⬜	🟩	🟦	🟦	🟩	🟦	⬜
Feed intake and utilization	⬜	🟦	🟦	🟦	🟩	🟦	🟦
Growth	⬜	🟦	🟦	🟦	🟦	🟦	🟦
Behaviour	⬜	🟦	🟦	🟦	🟩	🟦	🟦
Stress	⬜	🟦	🟦	🟦	🟩	🟦	🟦
Health and welfare	⬜	🟦	🟦	🟦	🟦	🟦	🟦
Viral disease	⬜	🟩	🟦	🟦	🟩	🟩	🟩
Bacterial disease	⬜	🟩	🟦	🟦	🟩	🟩	🟦
Parasitic infection: Sea Lice	⬜	🟩	🟦	🟦	🟦	🟩	🟦
Parasitic infection: Ameobic Gill Disease (AGD)	⬜	🟩	🟦	🟦	🟩	🟦	🟦
Cleanerfish	⬜	🟦	🟦	🟦	🟩	🟦	🟦
Disease prevention and treatment	⬜	🟦	🟦	🟦	🟩	🟩	🟦
Mortalities	⬜	🟦	🟦	🟦	🟩	🟦	🟩
Harmful Algal Blooms (HABs)	⬜	🟦	🟦	🟦	🟦	🟦	🟦
Jellyfish	⬜	🟦	🟦	🟦	🟩	🟦	🟦
Other coastal users and activities	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Site availability, allocation and restrictions	🟩	🟩	🟩	🟩	🟩	🟩	🟩

[1] Broodstock salmon may be held in sea cages, for these fish the impacts will be the same as in the Growout phase

[2] Impact will depend on control of inlet water

[3] Broad category as impact will depend on control of inlet water

⬜ Not applicable
🟩 Potential link
🟦 Documented link

Fig 3. Matrix of impacts and climate stressors for production stages.

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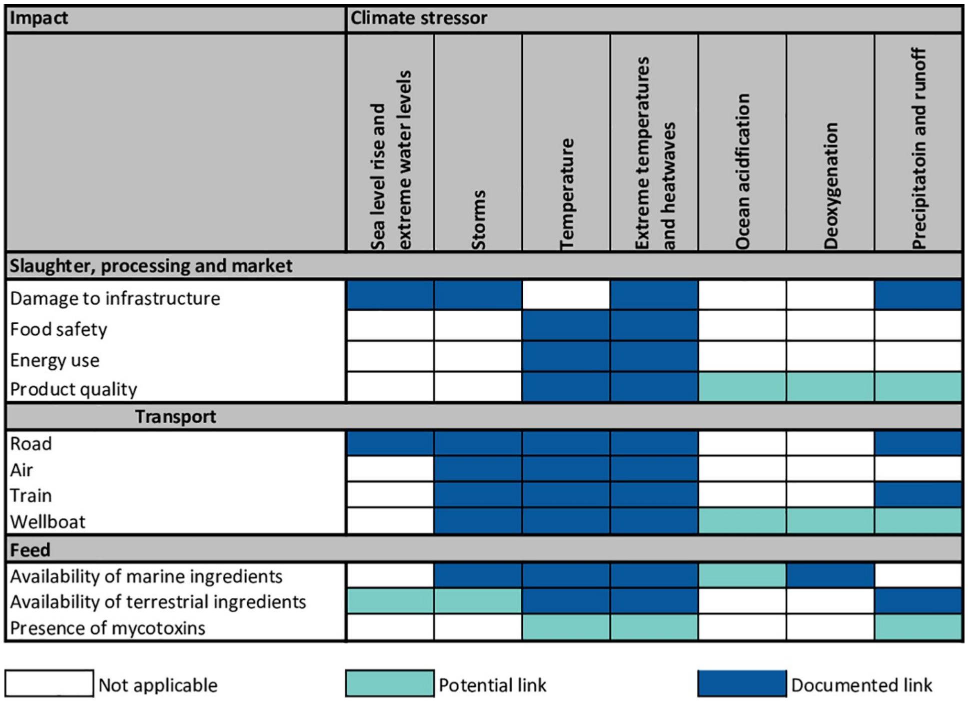
Availability of inlet water had 'Documented links' to 3 climate stressors (*Temperature*, *Extreme temperatures and heatwaves*, *Precipitation/runoff*). Temperature and precipitation will affect water availability in water sources (e.g., rivers, lakes, groundwater). Results from modelling studies suggest the duration of droughts in some parts of the country will increase in the future due to increasing summer temperatures leading to increased evaporation [35,64,69]. Increased droughts could lead to reductions in water levels and streamflow, which may affect the availability of water for hatchery systems. Some areas will experience increased precipitation and runoff, as well as increased snowmelt, which may result in increased water levels [35], depending on the location and the time of year. Both RAS and flow through systems would be affected by water availability, though RAS have much lower water demands since they reuse a high proportion of their water [70].



Impact	Climate stressor						
	Sea level rise and extreme water levels	Storms	Temperature	Extreme temperatures and heatwaves	Ocean acidification	Deoxygenation	Precipitatoin and runoff
Slaughter, processing and market							
Damage to infrastructure	🟦	🟦	⬜	🟦	⬜	⬜	🟦
Food safety	⬜	⬜	🟦	🟦	⬜	⬜	⬜
Energy use	⬜	⬜	🟦	🟦	⬜	⬜	⬜
Product quality	⬜	⬜	🟦	🟦	🟩	🟩	🟩
Transport							
Road	🟦	🟦	🟦	🟦	⬜	⬜	🟦
Air	⬜	🟦	🟦	🟦	⬜	⬜	⬜
Train	⬜	🟦	🟦	🟦	⬜	⬜	🟦
Wellboat	⬜	🟦	🟦	🟦	🟩	🟩	🟩
Feed							
Availability of marine ingredients	⬜	🟦	🟦	🟦	🟩	🟦	⬜
Availability of terrestrial ingredients	🟩	🟩	🟦	🟦	⬜	⬜	🟦
Presence of mycotoxins	⬜	⬜	🟩	🟩	⬜	⬜	🟩

⬜ Not applicable 🟩 Potential link 🟦 Documented link

Fig 4. Matrix of impacts and climate stressors for stages in post-production and wider supply chain.

https://doi.org/10.1371/journal.pclm.0000017.g004

Inlet water quality had 'Documented links' to 4 climate stressors (*Temperature*, *Extreme temperatures and heatwaves*, *Deoxygenation*, *Precipitation/runoff*). Temperature and oxygen are important parameters for hatcheries and early stages [70–73], and it is important that conditions are kept within optimal ranges, and gradual temperature increases as well as heatwaves could affect inlet water quality. Changes in rainfall may also affect inlet water quality, for example runoff could lead to increased suspended solids [70], or metal contamination [74].

Energy use also had 'Documented links' to 4 climate stressors (*Temperature*, *Extreme temperatures and heatwaves*, *Deoxygenation*, *Precipitation/runoff*). Lower water availability will lead to increased water recirculation, which involves more energy use [75]. Likewise, control of temperature, oxygen levels, and water quality (e.g. through cooling systems, heaters, oxygen pumps, and filtration etc) will use more energy [76,77].

Breeding programs are an important part of salmon aquaculture as they are used to improve key production traits [78,79]. While they are often considered a possible adaptation response, climate change may also impact breeding programs. There were 'Documented links' to 3 climate stressors (*Temperature*, *Extreme temperatures and heatwaves*, *Deoxygenation*). Breeding program managers need to know what the desired traits are and what the potential future conditions could be. Most breeding programs have focused on faster growth [78] and growth is strongly influenced by temperature and oxygen [80,81], so these climate stressors will affect decisions on breeding strategies. However, it is also important to understand the trade-offs in trait selection, as recent work on rainbow trout has suggested that resistance to hypoxia and resistance to temperature are linked to two genetically different traits [82]. Breeding programs also had 'Potential links' to 2 climate stressors (*Ocean acidification*, *Precipitation/runoff*). Although ocean acidification and changes in precipitation/runoff are linked to several impacts in later stages, it is unclear if breeding programs would focus on these impacts, so these were considered 'Potential'. Overall, the uncertainty of future conditions is a challenge, as chosen breeding goals may be inappropriate for the complexities the industry will face in the future [83].

The broodstock management impact refers to broodstock when held in land-based facilities. Broodstock management had 'Documented links' to 2 climate stressors (*Temperatures*, *Extreme temperatures and heatwaves*). Water temperatures can affect broodstock performance [84], and stress can affect offspring survival, growth, and malformations [85]. King et al. [86] showed there was a significant reduction in fertility and survival of ova from broodstock held at higher temperatures. Higher temperatures have been shown to inhibit milt production and ovulation [87,88]. Broodstock management had 'Potential links' to 3 climate stressors (*Ocean acidification*, *Deoxygenation*, *Precipitation/runoff*). Although most studies focus on temperature, other environmental factors affect reproductive development and spawning, and changes in water quality may affect the health and welfare of the broodstock [89]. Broodstock salmon may however be held in sea cages until they are ready to spawn, and those salmon would experience the same impacts as the fish in the *Growout* stage, highlighting the importance of not looking at impact in a siloed way and the need to consider the entire production system.

Gamete quality and early development had 'Documented links' to 3 climate stressors (*Temperature*, *Extreme temperatures and heatwaves*, *Deoxygenation*). Gamete quality is dependent on a number of factors including broodstock management and environmental conditions in the hatchery [71]. Temperature at egg stage affects muscle growth and condition factor later in life [90]. Sub-optimal conditions, such as low oxygen, during early development may have long-term effects through epigenetic changes [72]. Hypoxia can affect early development, lead to delayed hatching, reduced growth, deformities, and mortalities [73]. Gamete quality and early development had a "Potential link" to 1 climate stressor (*Precipitation/runoff*). Though most research has been done on temperature, there are other aspects of water quality that affect gamete quality [91], and changes in precipitation and runoff may affect the inlet water [92].

3.1.2 Juvenile production. There were 5 impacts identified within *Juvenile production* (Fig 3). As juvenile production facilities are similar to hatcheries (land-based flow through or RAS), there were 4 impacts (*Damage to infrastructure*, *Availability of inlet water*, *Water quality of inlet water*, *Energy use*) exposed in a similar way to the same climate stressors, so to avoid repetition, see Section 3.1.1. The fifth impact was a broad grouping 'Biological impacts' which was used as an overview of the potential biological considerations, and there were 'Documented links' to 4 climate stressors (*Temperature*, *Extreme temperatures and heatwaves*, *Deoxygenation*, *Precipitation/runoff*). These stressors are associated with the conditions in the juvenile production environment that are important for further growth and development, not only in this stage, but also later life. Increased temperatures and poor water quality may stress fish, impair development, and result in deformities [93–97]. Metal contamination in inlet water from precipitation/runoff affects the development of smolts and causes issues for seawater transfer [74,98,99].

3.1.3. Growout. The *Growout* phase had 22 identified impacts, which was the highest number compared to other stages (Fig 3). This is unsurprising since cages are open to the environment, directly exposing the fish to climate stressors. As a result, some of the impacts are more detailed than the other categories, but still include broad groupings due to the level of information that is available. The *Growout* stage assessment focused on coastal cage systems. Existing and future development and implementation of new production technologies such as closed containment systems, offshore cages and land-based RAS will affect the overall vulnerability in the *Growout* stage to climate stressors, but how and to what extent is uncertain.

Damage to land-based infrastructure would have the same links to stressors as in the previous production stages (Section 3.1.1. for an overview). Damage or failure of cage infrastructure had a 'Documented link' to 1 climate stressor (*Storms*). Storms have been shown to damage cages [100], sometimes leading to escape events [101]. Human safety issues and disruption of activities also had a 'Documented link' to 1 climate stressor (*Storms*). Rough conditions make it difficult to access farm sites and can lead to unsafe working conditions [102]. Holen et al. [103] showed the highest number of injuries occurred in autumn and winter months, when weather conditions are challenging.

Fouling of cage infrastructure had "Documented links" to 3 climate stressors (S*torms*, *Temperature*, *Extreme temperatures and heatwaves*). Storms could affect access to sites and the ability to clean nets, which is a common approach for biofouling control in Norway [104]. Fouling development is often associated with temperatures, with highest abundance in summer months and peak summer temperatures [105,106]. Fouling of cage infrastructure had "Potential links" to 3 climate stressors (*Ocean acidification*, *Deoxygenation*, *Precipitation/runoff*). Dobretsov et al. [107] reviewed studies and found mixed reports on the effect of ocean acidification on biofouling communities. Oxygen levels influence ecosystem structure, but effects on biofouling communities are complex, especially as species can be producers as well as consumers, of oxygen [107,108]. Changes in rainfall/runoff may affect nutrient levels in the water column which could affect biofouling populations, however there are still knowledge gaps about the role of nutrients from the surrounding area, as well as the role of aquaculture production, in biofouling development [109,110].

Dispersion and assimilation of wastes had 'Documented links' to 4 climate stressors (*Storms*, *Temperature*, *Deoxygenation*, *Precipitation/runoff*). Salmon farming releases wastes into the environment including uneaten feed and faeces, which can accumulate in the area underneath and surrounding the fish cages [111–113]. Storms can lead to sediment resuspension [114], although this will also depend on the depth of the site. Settling rates of wastes can vary depending on a number of factors including water viscosity (e.g. temperature and salinity) [115]. Many Norwegian salmon farms are located in fjords, and studies have shown that warming is leading to reduced oxygen levels in some areas [55]. Deoxygenation can reduce assimilative capacity [55,116]. Precipitation and runoff will contribute organic matter to the fjord or coastal environment and the associated microbial activity could affect overall assimilative capacity of the environment [117]. Dispersion and assimilation of wastes had a 'Potential link' to 1 climate stressor (E*xtreme temperatures and heatwaves*). While links between temperature and dispersion and assimilation of wastes have been established, the link with extreme temperatures and heatwaves is less clear.

Stocking density had 'Documented links' to 3 climate stressors (*Temperature*, *Extreme temperature and heatwaves*, *Deoxygenation*). The maximum allowable biomass (MAB) at a farm is defined by regulations and licences [118], nevertheless optimal density varies depending on life stage, water quality, feed strategy, management practices and design of the system [119,120]. Salmon adjust their position in the cage depending on temperature and oxygen, and may crowd in certain areas [13,121]. High densities can have negative consequences for health and welfare [121–123]. Consequently, increased temperature and decreased oxygen could lead to farm managers reducing stocking density to improve health and welfare, and overall growth and production. Stocking density had 'Potential links' to 2 climate stressors (*Storms*, *Ocean acidification*). During storms, high stocking densities could mean greater risk of collisions, but there is limited information or demonstratable examples that link storms to stocking density. It is unclear if ocean acidification would affect salmon behaviour (see behaviour impact), and thus, it is uncertain if there would be implications for stocking density.

Feed intake and utilization had "Documented links" to 5 climate stressors *(Storms*, *Temperature*, *Extreme temperatures and heatwaves*, *Deoxygenation*, *'Precipitation / runoff'*). Feed is usually supplied through automated feeders, but if conditions are too stormy, then distribution of feed could be affected, and/or salmon behaviour and feed intake changed [124]. The link between feed intake, utilization and temperature is well documented [80,125,126]. During a heatwave event in Tasmania, salmon reduced feed intake and stopped feeding [127]. Maximal feed intake is also affected by oxygen and temperature and may also be size-dependent [81]. The microbiota in the gastrointestinal tract play an important role in fish nutrition, growth and health [128], and temperature, salinity and other aspects of water quality can all influence the diversity of species within the gut [129,130]. Feed intake and utilization had a 'Potential link' to 1 climate stressor (*Ocean acidification*). Cominassi et al. [131] showed that restricted feed intake exacerbated effects of increased temperatures and ocean acidification, but research is needed on whether ocean acidification would impact feed intake and utilization.

Growth had "Documented links" to 6 climate stressors (*Storms*, *Temperature*, *Extreme temperatures and heatwaves*, *Ocean acidification*, *Deoxygenation*, *Precipitation/runoff*). Storms can create challenging conditions for salmon. If current speeds are too strong then salmon spend more energy on swimming, which could lead to reduced growth potential [124,132,133]. Temperature is the main environmental factor influencing salmon growth [80]. Extreme temperatures and heatwaves also affect growth [127], although it will depend on the duration and magnitude of the event. Oxygen is also an essential factor, with low oxygen levels negatively affecting growth [81]. Few studies have considered salmon aquaculture and ocean acidification, although in a short-term experiment, McCormick and Regish [134] found an increased growth rate in fish held in higher CO_2 conditions. Most other studies have considered CO_2 for land-based systems, and shown that as CO_2 increases, the growth rate will decrease [135,136]. Thus, although this was considered a 'Documented link', as there is a link between the stressor and impact, further research is required into the effects of ocean acidification on salmon growth. Salinity is not considered a major factor that affects growth rate, although there is a link, Handeland et al. [137] indicated there may be some long-term growth advantages of lower salinity. As mentioned in Feed intake and utilization, environmental factors such as temperature and salinity can affect gut microbiota, with implications for salmon growth [129,130].

Behaviour had 'Documented links' to 5 climate stressors (*Storms*, *Temperature*, *Extreme temperature and heatwaves*, *Deoxygenation*, *Precipitation/runoff*). Storms affect fish behaviour as fish adjust their position in cages in response to waves and currents [124]. Salmon individuals and groups have shown avoidance to high and low temperatures, indicating active behavioural thermoregulation [138,139]. During a heatwave event, salmon were observed moving to deeper and colder waters within the cage [140]. Salmon also move in response to oxygen levels [138,141,142], and have salinity preferences [13]. Oppedal et al. [13] noted that turbidity, as a potential consequence of runoff, has been suggested as a factor influencing salmon swimming behaviour but no studies were found that demonstrate this. Behaviour had a 'Potential link' to 1 climate stressor (*Ocean acidification*). The impact of ocean acidification on fish behaviour is a source of debate amongst researchers [143], and there is a need for further work on salmon.

Stress had 'Documented links' to 5 climate stressors (*Storms*, *Temperature*, *Extreme temperature and heatwaves*, *Deoxygenation*, *Precipitation/runoff*). Bad weather conditions and storms, resulting in high waves and fast current speeds can increase stress in salmon kept in sea cages [144]. Increased temperatures and decreased oxygen levels are also known to stress salmon [13,142]. Transcriptomics revealed stress responses in salmon following periods of extreme temperatures and heatwaves, and upon periods with low levels of oxygen [145–147]. Runoff could lead to increased suspended solids and decreased water quality, which could stress the salmon [92,148]. Stress had a 'Potential link' to 1 climate stressor (*Ocean acidification*). As highlighted previously, there are few studies on ocean acidification and salmon, and it is unclear if ocean acidification would be linked to stress.

Health and welfare had 'Documented links' to 6 climate stressors (*Storms*, *Temperature*, *Extreme temperatures and heatwaves*, *Ocean acidification*, *Deoxygenation*, *Precipitation/*

runoff). This is a broad impact category as stressors may affect many specific aspects of health and welfare, each of which could be explored at length, but since the intention of this study is to demonstrate the range of considerations across salmon production, a summary category highlighting some of the major issues, and demonstrating complexity of this area was considered more appropriate. Storms and high current speeds can lead to wounds and fin damaged due to collisions [144]. Temperature is known to be linked to health and welfare, for example the development of cataracts [95] and cardiac health [149]. Furthermore, Sundh et al. [150] showed that reduced or fluctuating levels of dissolved oxygen and high temperatures cause primary and secondary stress responses and that the intestinal barrier function is reduced. It is difficult to know the implications of multiple stressors, for example, skin is strengthened after transfer to sea, and this could be temperature related [151], but lower pH reduces the barrier strength of skin [136] and increased temperature reduces the barrier strength and the alters the morphology of the skin [123,152]. Gill health is a priority for salmon aquaculture, since gills are responsible for many critical physiological functions [153] and are in direct contact with the water, and therefore susceptible to environmental conditions, water quality changes, and infection [154–156]. In acid rain experiments, Finstad et al. [157] showed that plasma chloride levels were elevated in fish from the high acid and moderate acid groups compared to reference groups. However, there is a need for more research into the effects of ocean acidification on salmon health and welfare, particularly regarding gill health [158].

Viral diseases had 'Documented links' to 2 climate stressors (*Temperature*, *Extreme temperatures and heatwaves)*. Viral diseases include cardiomyopathy syndrome (CMS), Pancreas Disease (PD), Infectious salmon anaemia (ISA), Infectious pancreatic necrosis (IPN) and Heart and Skeletal Muscle Inflammation (HSMI) [159]. There are known links between temperatures and some viral diseases, although the nature of the influence of temperature varies. Stene et al. [160] showed that seasonal increases in sea temperature triggered outbreaks of PD, whereas higher temperatures at sea transfer decreased the risk of IPN [161]. Additionally, for some diseases such as CMS, fast growth may be a contributing factor for developing a disease [162] and increased sea temperatures could result in faster growth in some areas, thus indirectly increasing incidences of CMS. Viral diseases were 'Potentially linked' to 4 climate stressors (*Storms*, *Ocean acidification*, *Deoxygenation*, *Precipitation/runoff)*. The hydrodynamic conditions within an area and connectivity between farms will influence the spread of viruses such as PD [163], but it is unclear what effect storms would have on transmission. Environmental stress (e.g. suboptimal water quality) may also increase risk for diseases such as CMS and HSMI [162,164], and may also increase mortalities [164]. Furthermore, salmon suffering from disease may have reduced tolerance to suboptimal conditions, for example salmon suffering from HSMI have reduced hypoxia tolerance [165]. The immune response of fish is also affected by temperature and oxygen [166], which could affect susceptibility to viral diseases.

Bacterial diseases had 'Documented links' to 3 climate stressors (*Temperature*, *Extreme temperatures and heatwaves*, *Precipitation/runoff*). Bacterial diseases and problems include furunculosis, Yersiniosis, Mycobacteriosis, Moritella, Tenacibaculum [159]. There are clear links between temperature and bacterial diseases affecting salmon, for example higher temperatures are risk factors for furunculosis [167] and Tenacibaculosis [168], whilst low temperatures are a risk factor for winter ulcer disease which is caused by the bacterium *Moritella viscosa* [169,170]. Salinity is also an important factor that influences some bacteria including *M. viscosa* [170]. However, it is important to note that the development of vaccines, in combination with good hygiene, led to a significant reduction of outbreaks of some bacterial diseases such as furunculosis [159,171]. Bacterial diseases had 'Potential links' to 3 climate stressors (*Storms*, *Ocean acidification*, *Deoxygenation*). Storms could increase contact between salmon and/or increase spread of pathogens which may increase transmission of bacterial diseases, but there are many uncertainties about this. As low oxygen (and high temperature) affect the immune status of the fish [166], it may increase susceptibility for bacterial infections, but further research is necessary.

There are a number of parasites that affect Norwegian salmon aquaculture, and also cleanerfish [159]. Two of the most serious infections (sea lice, amoebic gill disease (AGD)) were included here. Parasitic infection (sea lice) had 'Documented links' to 4 climate stressors (*Temperature*, *Extreme temperatures and heatwaves*, *Ocean acidification*, *Precipitation/runoff*). The main species of sea lice that affects Norwegian aquaculture is *Lepeophtheirus salmonis*, although *Caligus elongatus* is also an issue at some locations. Temperature and salinity play an important role in the development, reproduction, and life history of sea lice [172–174], and infection pressure is predicted to increase in the future due to increased temperatures [175]. Extreme temperatures and heatwaves will affect sea lice as development is significantly faster at high temperatures [173]. Lice number is also affected by acidic condition with higher densities found at lower pH compared to a reference group [157], and studies suggest sea lice are tolerant of end-of-century conditions [176]. Parasitic infection (sea lice) had 'Potential links' to 2 climate stressors (*Storms*, *Deoxygenation*). The spread of lice is influenced by temperature and currents [177], so storms and resulting waves and strong currents could influence the spread of sea lice (e.g. Wright et al. [178] found new infestations after a storm event), but this will depend on site characteristics and connectivity between farms, so it is only considered 'Potential'. It is unclear what effects deoxygenation would have on sea lice, although since oxygen levels can influence the immune system [166] then deoxygenation may affect susceptibility to sea lice infection.

Parasitic infection (Amoebic Gill Disease–AGD) had 'Documented links' to 4 climate stressors (*Temperature*, *Extreme temperatures and heatwaves*, *Deoxygenation*, *Precipitation/runoff*). AGD is caused by the amoeba *Neoparamoeba perurans* [179]. Although the disease has been a problem in Tasmania since the 1980's, it was first observed at several farms on the West coast of Norway in 2006, when temperatures were higher than average [180]. It was not seen again until 2012 but has now become a major issue for the Norwegian industry [159]. The two most important risk factors for outbreak of AGD are considered to be seawater temperatures and high salinity [159,181,182]. Reduced oxygen levels are also a risk for gill health [158], and AGD infected fish have been shown to have reduced survival in hypoxic conditions [183,184]. Oldham et al. [184] found that hypoxic conditions accelerate the progression of AGD but noted there are still uncertainties about effects of hypoxia on AGD susceptibility. Parasitic infection (AGD) had 'Potential links' to 2 climate stressors (*Storms*, *Ocean acidification*). Storms could play a role in movement of the amoeba but, as highlighted by Oldham et al. [179], there are still many knowledge gaps about *N*. *perurans* in the natural environment. More acidic conditions could have implications for gill health and AGD but further research is required into this [158].

Cleaner fish had 'Documented links' to 5 climate stressors (*Storms*, *Temperature*, *Extreme temperature and heatwaves*, *Deoxygenation*, *Precipitation/runoff*). Wrasse and lumpfish are used in salmon aquaculture as a biological control mechanism to reduce sea lice levels. One of the challenges of growing different species within the same environment is the different biology, life histories and environmental tolerances. For the cage environment conditions in which salmon are farmed, ballan wrasse are thought to be less robust than salmon [185]. Lumpfish are poor swimmers [186,187], and may therefore be affected by storms and increased current speeds. Wrasse are less effective at lower temperatures and become inactive in winter so lumpfish are considered a more appropriate species in many parts of Norway [188]. However, lumpfish prefer low temperatures [189,190], and cannot survive extended periods above 18˚C [186]. Hvas and Oppedal [187] showed that lumpfish are less sensitive to low oxygen levels than salmon, though lumpfish are slower in responding to sudden changes than salmon. Cleaner fish also have salinity preferences, with lumpfish selecting considerably lower salinities than wrasse [191], with the latter having a low tolerance for freshwater [192]. Cleaner fish also had a 'Potential link' to 1 climate stressor (*Ocean acidification*). There are few studies on ocean acidification and cleanerfish. Sundin and Jutfelt [193] evaluated behavioural impact of increased CO_2 on the goldsinny wrasse (*Ctenolabrus rupestris*), one of the species used as cleaner fish, and found few effects, suggesting behavioural tolerance to high CO_2 levels. However, the authors note that other studies show there is variation in effects between fish species [193]. Thus, the link was considered 'Potential'.

Disease prevention and treatment had 'Documented links' to 4 climate stressors (*Storms*, *Temperature*, *Extreme temperatures and heatwaves*, *Precipitation/runoff*). Storms can affect access to site and create difficult working conditions which may affect the ability to treat or use preventative measures, for example Wright et al. [178] tested snorkel technology at a cage site but an intense storm event damaged the equipment. Mortality rates for most delousing methods increases with rising temperature [194]. Some treatment methods should not be used above certain temperatures, for example hydrogen peroxide should not be used to treat AGD above 13.5˚C [179,195]. Water quality and salinity may also affect disease prevention and treatment strategies, e.g. Oppedal et al. [196] found that salinity was a major factor affecting the efficacy of snorkel technology. Disease prevention and treatment had 'Potential links' to 2 climate stressors (*Ocean acidification*, *Deoxygenation*). As shown previously, ocean acidification and deoxygenation may be linked to different aspects of salmon health and so these stressors may also potentially be linked to disease prevention and treatment.

Mortalities had 'Documented links' to 4 climate stressors (*Storms*, *Temperature*, *Extreme temperatures and heatwaves*, *Deoxygenation*). Storm events can result in mortalities [197] and this is a high risk for younger and less robust fish following transfer to sea water. Waves and strong currents may lead to net deformation, reducing available space for the fish and leading to mortalities [198]. Mortalities occur at high temperatures [80,199]. In 2019 there was a multi-factorial mass mortality event at salmon farms in Canada and two of the drivers were prolonged increased temperatures above 18˚C and reduced oxygen levels [200]. Mortalities had 'Potential links' to 2 climate stressors (*Ocean acidification*, *Precipitation/runoff*). As ocean acidification and rainfall/runoff are (or potentially) linked to other physiological and health impacts it is difficult to say there would be no effect, but there is insufficient information at present on direct impact on mortality.

Harmful Algal Blooms (HABs) had 'Documented links' to 6 climate stressors (*Storms*, *Temperature*, *Extreme temperatures and heatwaves*, *Ocean acidification*, *Deoxygenation*, *Rainfall/runoff*). Temperature, pH, nutrient availability, deoxygenation, and regional and local hydrodynamics all affect the occurrence of HABs [201–203], and extreme storms and precipitation events have also been directly and indirectly linked to HAB events [204,205]. Due to the multifactorial nature of HABs it is difficult to predict future occurrences, however the general consensus is that HAB occurrences are increasing in abundancy and frequency, and their range is expanding, with species being found in new areas [201]. In Norway, a range of algae species have been responsible for fish kills, most recently the *Chrysochromulina leadbeateri* bloom in 2019 that resulted in over USD$100 million losses [206]. As noted by Karlson et al. [206], a previous bloom of *C. leadbeateri* in 1991 also resulted in substantial losses, but as there was a long time period between the events and monitoring of conditions was inconsistent, it is difficult to identify trends. So, although the links between stressors and HABs are known, there are still many uncertainties in how HAB distributions and frequency of events will change, and it is very difficult to predict where and when blooms may occur.

Jellyfish had 'Documented links' to 5 climate stressors (*Storms*, *Temperature*, Extreme temperatures and heatwaves, *Deoxygenation*, *Precipitation/runoff*). Halsband et al. [207] highlight the lack of knowledge about distribution of jellyfish in Norwegian waters. At a global level there are also many uncertainties surrounding the potential impact of climate change on jellyfish. Mitchell et al. [208] suggest increasing frequency of severe storms in the North Atlantic may be a reason behind rising number of jellyfish blooms reported near salmon farms in Ireland. A review by Purcell et al. [209] noted that temperature and salinity affect abundance of some species, and many jellyfish are tolerant of very low oxygen levels. Studies elsewhere have shown jellyfish populations increase in hypoxic conditions while other species decrease [210], thus altering ecosystem structure. Extreme temperatures and heatwaves can affect jellyfish population dynamics, as shown by Chi et al. [211] for *Aurelia aurita*, a jellyfish found in Norway that is harmful to salmon [212]. Coastal runoff can contribute nutrients to the aquatic ecosystem, in some cases altering the food web which will have effects on jellyfish populations [209]. Furthermore, changes in precipitation and runoff can affect water clarity, and reduced transparency can benefit non-visual jellyfish over visual predator species [62]. Jellyfish had a 'Potential link' to 1 climate stressor (*Ocean acidification*). There is a lot of uncertainty and debate about the effects of ocean acidification on jellyfish [213], and it is unclear if it would impact jellyfish interactions with salmon aquaculture.

Other coastal users and activities had 'Potential links' to all 7 climate stressors (*Sea level rise*, *Storms*, *Temperatures*, *Extreme temperatures and heatwaves*, *Ocean acidification*, *Deoxygenation*, *Precipitation/runoff*). In addition to aquaculture, the Norwegian coastal zone is an extremely important area for many commercial and recreational activities, like fisheries, oil & gas, agriculture, surfing, and kayaking [214]. Changing environmental conditions in the coastal zone may affect the availability and suitability of areas for all activities, including aquaculture. Furthermore, there is increasing pressure on the coastal environment as stakeholders are demanding more space, including exclusive use of an area [214]. Changing requirements of other users may impact aquaculture as there may be increased conflict over space and fewer opportunities to expand, move or develop new sites. It is likely that stressors will be linked to impacts for other coastal users in some way, but each activity would have to do assessments, similar to the present one for salmon aquaculture, which is why all links were considered 'Potential'.

Site availability, allocation, and restrictions had 'Potential links' to all 7 climate stressors (*Sea level rise*, *Storms*, *temperatures*, *Extreme temperatures and heatwaves*, *Ocean acidification*, *Deoxygenation*, *Precipitation/runoff*). At present, a relatively large share of Norway's coastal waters is suitable for salmon aquaculture, as shown by the distribution of sites in Fig 1. However, biophysical changes to environmental conditions may affect the suitability of locations for aquaculture, as has been described in all impacts within this stage. Furthermore, sites and production restrictions are determined through political processes [215], and effects of climate change from all stressors on the sector and other users may affect the public and political perception of intensive salmon farming which could lead to changes in the allocation and regulation of licences, sites and operations. All of the links were considered 'Potential' as there is little information available to specifically link the climate stressors to site availability, allocation, and restrictions at present.

3.1.4. Slaughter and processing.

The *Slaughter and processing* stage had 4 identified impacts that were linked to several climate stressors (Fig 4). Similar to salmon aquaculture production facilities, slaughterhouses are found along the coastline (Fig 1), and climate stressors could damage infrastructure (See Section 3.1.1. for summary). Food safety had 'Documented links' to 2 climate stressors (*Temperature*, *Extreme temperature and heatwaves*). Foodborne pathogens and spoilage bacteria are a food safety risk with potential implications for human health and/or shelf life of products [216,217]. Good hygiene practices and temperature control are necessary to minimise risks of contamination [216]. As temperature control is required, Energy use was another identified impact and similar to food safety, had 'Documented links' to the same 2 climate stressors (*Temperature*, *Extreme temperature and heatwaves*). Cooling and freezing account for about 70% of the energy use in slaughterhouses and processing plants [218], and if temperatures increase, there may be increased need for cooling and energy.

Product quality had 'Documented links' to 2 climate stressors (*Temperature*, *Extreme temperatures and heatwaves*). Many slaughterhouses have sea cages to hold fish temporarily before slaughtering and processing. Even though salmon are held in these cages for a relatively short time, the environmental conditions are important as they will affect the quality of the product. For example, filet quality is dependent on slaughtering conditions, including time and temperature [219]. More severe gaping has been observed in stressed fish and at higher temperatures [220]. Product quality will also depend on conditions throughout the entire production cycle [221], but the impact is noticed in the processing stage and then implications for selling the product. At a salmon farm in Tasmania, Wade et al. [127] showed that a period of unusually high temperatures led to decreased flesh colour. Product quality also had 'Potential links' to 3 climate stressors (*Ocean acidification*, *Deoxygenation*, *Precipitation/runoff*). There is limited information on ocean acidification and product quality for any aquaculture species, there are some studies that have shown that nutritional quality of shellfish can be affected [222], but impacts on salmon are unknown. Low oxygen levels during growout have been shown to slightly affect rainbow trout flesh quality [223], but implications for salmon in cages are uncertain. While runoff may affect water quality and/or introduce contaminants to the environment [224,225], effects on product quality of salmon raised in Norwegian marine cage farming environments is unclear.

3.1.5. Transport. There were 4 impacts identified for the *Transport* stage (Fig 4). These were broad groupings based on the type of transport (Road, Air, Train and Wellboat) so each impact covers a wide scope. Road transport had 'Documented links' to 5 climate stressors (*Sea level rise and extreme water levels*, *Storms*, *Temperature*, *Extreme temperatures and heatwaves*, *Precipitation/runoff*). In low-lying coastal areas, storm surges and increased water levels due to sea level rise may affect road networks. Hazards of road transportation include accidents, especially in winter months [226], and the road network is often affected or damaged by winter floods, avalanches and landslides [227]. Heavy rainfall is one of the main triggers for landslides, although erosion, snowmelt and weathering of bedrock are also factors [67], and precipitation and rapid temperature changes are triggers for snow avalanches [68]. Increased temperatures may affect storage and transportation times. Salmon are sold either chilled or frozen and must be transported in refrigerated or frozen storage and there is an optimal time-temperature for the product from transport to retail to customer [228].

Air transport had 'Documented links' to 3 climate stressors (*Storms*, *Temperature*, *Extreme temperatures and heatwaves*). Bad weather and storm events can disrupt air transport and lead to flight delays [229] and such events are expected to increase in frequency. Increase in average and extreme temperature, resulting in decreased air density could potentially affect aircraft take-off performance and lead to weight restrictions [230,231]. There are similar issues to road transportation regarding refrigerated and frozen products.

Train transport had 'Documented links' to 4 climate stressors (*Storms*, *Temperature*, *Extreme temperatures and heatwaves*, *Precipitation/runoff*). Rail freight transport or road-rail intermodal freight transport is a strategy for reducing emissions compared to road or air transport and may be a more important strategy for goods transport in the future [232]. Storms, increased temperatures (average and sudden extremes), and precipitation/runoff contribute to landslides and avalanches, and this is a challenge for the railway network as some parts are located on sensitive clays susceptible to destabilisation [67,233]. Storms and heavy rainfall events have already led to serious damage in the Norwegian rail network [234]. Some areas with poor drainage may be more susceptible to flash floods which may result in rapid destruction of railway embankments [234]. There are similar issues to road and air transportation regarding refrigerated and frozen products.

Wellboats had 'Documented links' to 3 climate stressors (*Storms*, *Temperature*, *Extreme temperatures and heatwaves*). Poor weather conditions can affect operations such as filling or emptying ballast water, and loading and unloading of fish, as well as the actual transport route used to get to the destination [235]. Storms and bad weather create challenging working conditions, potentially affecting health and safety of the operators, as well as the welfare of the fish [236], and increase risk of escapes during transfers [102]. Wellboats can be used for open transport, where water is continually exchanged with surrounding water, and closed transport where water is recirculated in the boat [235]. Intake water is from the sea, therefore water quality at the source is very important. High temperatures of water within the wellboat could stress the salmon. Stress during transport from freshwater facilities to marine cages can lead to increased mortality following the transfer [237], and stress prior to slaughter can have negative impacts on product quality [219]. High temperatures are also unsuitable for treatments [238]. Furthermore, wellboats are a risk for disease transfer [235], and this could increase with rising temperatures eg. Bacterial diseases. Wellboats were also 'Potentially linked' to 3 climate stressors (*Ocean acidification*, *Deoxygenation*, *Precipitation/runoff*). It is unclear if there would be a link to an impact from ocean acidification as few studies have investigated this. Low oxygen levels are known to stress fish, but some boats have technology to control oxygen levels [235], and oxygen levels will vary by inlet source. Depending on the source of the inlet water, water quality may be affected by precipitation and runoff, but this is uncertain and likely to be area specific.

3.1.6. Feed. There were 3 impacts identified in the *Feed* section (Fig 4) which focused primarily on ingredients as uptake and utilization of feed by the salmon was considered in the production stages. Availability of marine ingredients had 'Documented links' to 4 climate stressors (*Storms*, *Temperature*, *Extreme temperature and heatwave*, *Deoxygenation*). In 2013, less than 30% of the diet of farmed Norwegian salmon was from marine sources [239], and this decreased further in 2016, where feed contained 25% of marine sources [240]. Increased storminess and waves could affect the number of days available for fishing [241]. Temperature is a major driver in the life cycle, abundance, and distribution of species used for marine ingredients [242–244]. Marine heatwaves have been shown to negatively affect the abundance, size and quality of small pelagic fish due to ecosystem changes and shifts in their diets [245,246]. Oxygen levels can affect the behaviour and distribution of fish species, although there is variation between species [247,248]. Availability of marine ingredients had a 'Potential link' to 1 climate stressor (*Ocean acidification*). There are uncertainties about how ocean acidification will affect fish stocks, some research suggests there will be effects, for example, early life stages of some fish species have been shown to be particularly vulnerable to increased ocean acidification which would affect populations [249,250], but there are also acknowledgments that there have been mixed results from experiments and many knowledge gaps remain [251]. Of course, in addition to climate stressors, fisheries management will also have a key role to play in future fish stocks [252]. Furthermore, it must also be acknowledged that the use of marine ingredients in salmon feed is declining [239,240], and work is underway on novel and alternative feed source; e.g. fish from the mesopelagic zone [253], insect meal [254,255], micro-algae [256], and engineered crops such as Camelina [257].

Availability of terrestrial ingredients had 'Documented links' to 3 climate stressors (*Temperature*, *Extreme temperature and heatwaves*, *Precipitation/runoff*). Terrestrial ingredients have become increasingly important in salmon diets and include crops like soy and rapeseed [239,240]. The links between plant growth and temperature and precipitation are long established, with each species having their own thermal range and water requirements. Model projections suggest suitable areas for rapeseed production in Europe will reduce in future due to changes in temperature and rainfall [258], and this could reduce the availability of rapeseed oil for salmon feeds. Increasing temperatures and changes in rainfall led to reductions in US soybean yields between 1994 and 2013, with temperature being the main driver [259]. Extreme temperatures and heatwaves can also have significant effects on the success of crops and overall yields [260]. Availability of terrestrial ingredients had 'Potential' links to 2 climate stressors (*Sea level rise and extreme water levels*, *Storms*). Extreme water levels and coastal flooding and storms will affect global crop production [261], albeit with geographical variations, but consequences for salmon feed are less clear and so links were considered 'Potential'. The major complexity for the availability of terrestrial ingredients is that salmon feed producers are a relatively small part of a large global market and climate change and increasing pressure on terrestrial agriculture for food, feed and energy, will influence global supply, market and demand.

Presence of mycotoxins had 'Potential links' to 3 climate stressors (*Temperature*, *Extreme temperature and heatwaves*, *Precipitation/runoff*). Mycotoxins are secondary metabolites, produced by moulds which can spoil aquaculture feed leading to disorders in fish, fish mortality, human health problems and economic losses [262,263]. Moulds can occur due to storage conditions including high humidity and temperature variations [263], so increased rainfall and changes in temperatures may increase presence of moulds and risk of mycotoxins. However, the links were considered potential as there are many knowledge gaps surrounding the presence of mycotoxins in aquaculture feeds and implications for fish and human health [262,263] and there is also a need for more research into mycotoxin mixtures in fish feeds and their combined effects [264].

3.2. Adaptation

In total 101 adaptation responses were identified; 32 biological responses (Table 4), 13 environmental responses (Table 5), 17 policy responses (Table 6), and 39 technical responses (Table 7). The number of adaptation responses varied between each stage (Table 8): 21 in *Breeding and Hatchery*, 20 in *Juvenile*, 74 in *Growout*, 18 in *Slaughter and Processing*, 15 in *Transport*, 14 in *Feed*.

The high number of adaptation responses in *Growout* compared to the other stages is unsurprising considering this is the stage with the highest number of impacts as it is highly exposed to natural conditions and climate change effects. Some adaptation responses were relevant for more than one impact (e.g. E13: "Develop new and improved climate models for potential future climate across multiple spatio-temporal scales" was associated with impacts across all 6 stages), while other responses were more focused and targeted at specific issues (e.g. B10: "Develop breeding programs to improve thermal tolerance of cleanerfish" was only associated with the cleanerfish impact in *Growout*), although there would be indirect effects on other impacts too which were not considered.

Industry, followed by researchers, had the highest number of adaptation responses across most stages. The notable exception is *Transport*, where researchers, government, and other organisations that are not solely focused on aquaculture, lead more adaptation responses. However, it is also important to recognise that while researchers have a high proportion of responsibility to develop adaptation responses, they also rely on funding from industry and government to do the work. Accordingly, industry and government also have a responsibility to fund and support research, and this needs to be recognised and included in business plans and future strategies. Multiple groups will also be directly responsible for some adaptation responses, and this will require co-operation.

Table 4. Biological adaptation responses.

ID	Adaptation responses	Responsible	Time	Resources	Setting
B1	Reduce handling of the salmon	I	S	MI	F
B2	Adjust feeding to encourage salmon to swim deeper	I	S	MI	F
B3	Adjust timing of seawater transfer	I	S	MI	F
B4	Grow larger smolts to reduce time at sea	I	S	MO	F
B5	Develop breeding programs for more robust salmon	I/R	L	MA	I
B6	Develop breeding programs to improve thermal tolerance of salmon	I/R	L	MA	I
B7	Develop breeding programs for more disease resistant salmon	I/R	L	MA	I
B8	Develop breeding programs and strategies to improve utilisation of feed	I/R	L	MA	I
B9	Develop breeding programs to improve thermal tolerance of cleanerfish	I/R	L	MA	I
B10	Develop breeding programs for more disease resistant cleanerfish	I/R	L	MA	I
B11	Improve techniques for developing sterile salmon	I/R	L	MA	I
B12	Improve thermal tolerance of triploid salmon	I/R	L	MO	I
B13	Improve availability and utilization of important nutrients in the diet	I	M	MO	I
B14	Develop and use feed for fish growing at higher temperatures	I	M	MO	I
B15	Evaluate use of novel and alternative feed sources such as insects and microalgae	I/R	L	MA	I
B16	Evaluate use of genetically modified feed ingredients	R/I/G	L	MA	I
B17	Use nutritional strategies to maximise endogenous production of important fatty acids	I/R	L	MA	I
B18	Investigate potential for other marine fish as a source of fishmeal and fish oil (e.g. mesopelagic)	I/R	L	MA	I
B19	Establish databases and communication platforms to share knowledge about risks of mycotoxin contamination	R	M	MO	I
B20	Evaluate availability of fish stocks for feed ingredients	R	L	MA	I
B21	Improve feeding technology and strategies	I	S	MO	I
B22	Improved treatment strategies for higher temperatures	I	M	MA	I
B23	Development of a wide range of new and improved treatment strategies	I/R	M	MA	I
B24	Development of vaccines for salmon	R	L	MA	I
B25	Development of vaccines for cleanerfish	R	L	MA	I
B26	Use of epigenetics to improve salmon robustness	R	L	MA	I
B27	Use nutritional programming to improve feed intake and dietary choices	R	L	MA	I
B28	Use epigenetics to improve temperature tolerance	R	L	MA	I
B29	Develop broodstock management/conditioning approaches to improve egg and juvenile quality	R	L	MA	I
B30	Develop approaches for conditioning/imprinting to improve response to climate stressors	R	L	MA	I
B31	Investigate potential to exercise smolt to improve overall tolerance of conditions	I/R	M	MO	I
B32	Strengthening outer barriers through feed and exercise	I/R	M	MO	I

Note: Responsible (I = Industry, R = Researcher, G = Government, O = Other), Time (S = Short, M = Medium, L = Long), Resources (Mi = Minor, Mo = Moderate, Ma = Major), Setting (F = Farm, I = Industry, E = External).

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In the production stages (*Breeding and Hatchery*, *Juvenile*, and *Growout*), there were a number of adaptation responses that would require a short time and minor resources to develop and implement. This is due to the importance of ensuring optimal conditions in the production environment for farmed salmon, thus innovations have already been developed to reduce the risk of environmental stressors that can also be used for climate change adaptation. However, there were also adaptation responses, particularly in the *Growout* stage, that would require a long time and major resources.

4. Discussion

This study has shown that in a changing climate, there are species and area specific complexities that industry and associated stakeholders must consider within their short and long-term

Table 5. Environment adaptation responses.

ID	Adaptation responses	Responsible	Time	Resources	Setting
E1	Use of spatial models to select most suitable sites	R/I/G	M	MO	I
E2	Develop communication platforms for dissemination and implementation of knowledge	R/I/G	S	MO	I
E3	Identify sites that have a lower risk of fouling	I/R	M	MO	I
E4	Identify organisms for biological control of fouling communities	I/R	M	MO	I
E5	Develop and improve models for assessing waste dispersion	R	M	MO	I
E6	Develop Integrated Multi-Trophic Aquaculture (IMTA)	I/R	L	MO	I
E7	Identify sites where water availability would not be adversely affected by climate	I/R	M	MO	I
E8	Develop and improve early warning systems for extreme events	G/R	L	MA	E
E9	Improve jellyfish/HAB detection and monitoring	R/I/G	M	MA	E
E10	Develop predictive models for Jellyfish and HABs	R/I/G	M	MA	E
E11	Develop models for forecasting extreme weather events and storms	R	L	MA	E
E12	Improve flood warning systems	R/G	L	MA	E
E13	Develop new and improved climate models for potential future climate across multiple spatio-temporal scales	R	L	MA	E

Note: Responsible (I = Industry, R = Researcher, G = Government, O = Other), Time (S = Short, M = Medium, L = Long), Resources (Mi = Minor, Mo = Moderate, Ma = Major), Setting (F = Farm, I = Industry, E = External).

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plans. The Norwegian salmon aquaculture knowledge base presented here focuses on links between climate stressors and impacts, as well as possible adaptation responses. The links between climate stressors and impacts were categorised based on the evidence from published literature and industry news. The strength of the link and the adaptation categories were based on the authors' interpretations of the information, and there is naturally some subjectivity in this, but the narrative review style of the analysis section, as well as the S1 Appendix, provides

Table 6. Policy adaptation responses.

ID	Adaptation responses	Responsible	Time	Resources	Setting
P1	Train people in Health and Safety procedures	I	S	MI	F
P2	Develop action plans to respond to human health hazards	I	S	MI	F
P3	Develop action plans to respond to fish health hazards	I	S	MI	F
P4	Train people in emergency response procedures	I	S	MI	F
P5	Review and revise regulation on potential feed ingredients	G	S	MO	I
P6	Evaluate social and environmental risk/benefits of alternative and alternative feed ingredients	G	L	MO	I
P7	Review, update and implement technical standards for farm infrastructure	G	S	MI	I
P8	Review and revise health and safety legislation	G	S	MI	I
P9	Develop a more flexible licensing and regulatory processes for site allocation and changing sites	G	S	MO	I
P10	Improve local economic ripple effects	I/G	M	MI	I
P11	Improve consumer perception	I	L	MA	I
P12	Identify alternative transport routes	I	S	MI	I
P13	Review and update marine spatial plans regularly	G/I/O	S	MI	E
P14	Develop communication and knowledge sharing platforms between fisheries sector and feed producers	I/O	S	MO	I
P15	Develop communication and knowledge sharing platforms between agriculture sector and feed producers	I/O	S	MO	I
P16	Develop extreme weather risk assessments for transport network	G/R	M	MO	E
P17	Develop improved management of treatment procedures	I	M	MA	I

Note: Responsible (I = Industry, R = Researcher, G = Government, O = Other), Time (S = Short, M = Medium, L = Long), Resources (Mi = Minor, Mo = Moderate, Ma = Major), Setting (F = Farm, I = Industry, E = External).

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Table 7. Technical adaptation responses.

ID	Adaptation responses	Responsible	Time	Resources	Setting
T1	Improve feed storage facilities	I	S	MI	F
T2	Develop and install more robust cage infrastructure that can withstand storm events	I	S	MO	F
T3	Use of double nets to minimise risk of escapes	I	S	MI	F
T4	Use of remote operations and precision farming techniques	I/R	L	MA	F
T5	Use of coatings and antifouling cage materials	I	S	MI	F
T6	Use of mechanical removal technology to control fouling	I	S	MI	F
T7	Develop better monitoring techniques for biofouling	I	M	MO	F
T8	Use cages with deeper nets	I	S	MI	F
T9	Use oxygen pumps	I	S	MI	F
T10	Use tarpaulins to minimise contact with salmon	I	S	MI	F
T11	Use lice skirts	I	S	MI	F
T12	Install and use lights to encourage fish to swim deeper	I	S	MI	F
T13	Install pump systems to dilute algae/jellyfish	I	S	MI	F
T14	Use of real-time sensors and computer database platforms to monitor conditions and store data	I	L	MA	F
T15	Install pumps for deep water upwelling in sea cages to reduce temperature, increase oxygen, and reduce lice levels	I	S	MI	F
T16	Use of snorkel sea cage technology	I	M	MO	F
T17	Use technology to control temperature	I	S	MI	F
T18	Upgrade buildings so they are more robust and weather-proof	I	M	MO	F
T19	Construct effective barriers and flood control systems	I	S	MI	F
T20	Improve exploitation of by-products	R	M	MA	I
T21	Develop submersible cage technology	I/R	L	MA	I
T22	Develop semi-closed containment systems	I/R	M	MA	I
T23	Develop closed containment systems	I/R	L	MA	I
T24	Develop land-based RAS systems	I/R	L	MA	I
T25	Develop offshore cage technology	I	L	MA	I
T26	Develop barriers and repellents such as bubble nets	I/R	M	MO	I
T27	Convert freshwater flow-through systems to fully recirculating aquaculture systems	I	S	MI	I
T28	Develop more cost and energy efficient temperature control systems	I/R	M	MO	I
T29	Investments in renewable energy driven systems	I	S	MO	I
T30	Install water quality monitoring and alert systems for inlet sources	I	S	MI	I
T31	Develop improved inlet water treatment systems	I	S	MO	I
T32	Improve slaughter and processing techniques to maintain product quality	I	M	MO	I
T33	Develop more efficient technology to monitor and control water quality in wellboats	I	S	MO	I
T34	Construct wellboats that can operate in more exposed conditions	I	M	MA	I
T35	Improve storage and transportation conditions	I	L	MA	I
T36	Develop new and improved roads	G/O	M	MA	E
T37	Improved railway infrastructure	G/O	M	MA	E
T38	Improved drainage systems to reduce risks to transport infrastructure from flash flooding	G/O	M	MO	E
T39	Increase monitoring and maintenance of transport infrastructure	G/O	S	MO	E

Note: Responsible (I = Industry, R = Researcher, G = Government, O = Other), Time (S = Short, M = Medium, L = Long), Resources (Mi = Minor, Mo = Moderate, Ma = Major), Setting (F = Farm, I = Industry, E = External).

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context behind these decisions. This study is not intended to be an endpoint, instead it is a foundation on which others can, and should, build. There may be some stressors, impacts, and adaptation responses that have been overlooked due to limitations in the searches or insufficient information. This is not surprising given the multi-factorial and interdisciplinary nature

Table 8. Adaptation responses per stage.

Stage	Type of response	Response ID
Breeding and hatchery	Biology	B5, B29
	Environment	E7, E8, E11, E12, E13
	Policy	P1, P2, P3, P4
	Technology	T17, T18, T19, T27, T28, T29, T30, T31, T36, T39
Juvenile	Biology	B5, B29
	Environment	E7, E8, E11, E12, E13
	Policy	P1, P2, P3, P4
	Technology	T18, T19, T27, T28, T29, T30, T31, T36, T39
Growout	Biology	B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, B11, B12, B13, B14, B17, B21, B22, B23, B24, B25, B26, B27, B28, B30, B31, B32
	Environment	E1, E2, E3, E4, E5, E6, E8, E9, E10, E11, E12, E13
	Policy	P1, P2, P3, P4, P7, P8, P9, P10, P11, P13, P17
	Technology	T2, T3, T4, T5, T6, T7, T8, T9, T11, T10, T12, T13, T14, T15, T16, T18, T19, T21, T22, T23, T24, T25, T26, T36, T39
Slaughter and processing	Biology	B6, B14, B28
	Environment	E8, E11, E12, E13
	Policy	P1, P2, P4
	Technology	T17, T18, T19, T28, T29, T32, T36, T39
Transport	Biology	B23
	Environment	E8, E11, E12, E13
	Policy	P12, P16, P17
	Technology	T33, T34, T35, T36, T37, T38, T39
Feed	Biology	B8, B15, B16, B17, B18, B19, B20
	Environment	E13
	Policy	P5, P6, P14, P15
	Technology	T1, T20

For details on the responses see Tables 4–7.

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of aquaculture, as well as the rate of knowledge generation and innovation in the Norwegian salmon industry [265]. The key message from this work is that there are many real-world complexities that affect aquaculture production and wider supply chains that need to be considered for effective responses to future challenges.

The research presented here did not go as far as other studies that do full risk assessments (e.g. [266,267]), where climate change risk is expressed as a value, often calculated by a combination of impact and likelihood scores [268]. To enable an effective response to many of the challenges, an assessment requires site and company specific information, since impacts are affected by the varying farm management strategies and local conditions. For example, an increase in temperature in the north of the country will have different impacts than in the south [29] so one single risk score would not represent conditions and impacts throughout the country. Furthermore, as highlighted in the analysis here, and by others [19,269], aquaculture is an example of an industry where it is often difficult to disentangle climate change effects from other factors. This can be further complicated by different perceptions over what constitutes a risk [270], often depending on organisational priorities and available resources. These complexities make it difficult to generalise scores in a way that is relevant to all organisations and highlights a need for more targeted and detailed assessments. However, whilst climate change risk reporting is becoming important in many businesses [17], developing climate change risk assessments can be complex and time-consuming, especially when starting from scratch. Thus, a pre-assessment stage, that involves collating information on a wide range of possible considerations, as in this study, provides a starting point for individuals or companies to prepare their own assessments using their specific information with an appreciation of the level of detail and scope required. In this present study, the authors chose not to do a formal scoping or systematic review to identify and synthesise the information. A strict systematic review would have missed some of the important information that was in studies, grey literature, and news articles that were not found through database searches using keywords. For example, strict searches of salmon aquaculture studies do not reveal the link between storms and land-based infrastructure damage, but this is known to be an issue in coastal areas of Norway (e.g. [66]), so this could be a risk to the aquaculture sector. Thus, to cover the wide range of potential impacts and adaptation responses, searches guided by authors' experience and general information from stakeholders, examinations of cited documents from within studies, and consultations of non-academic documents and industry news articles, were all deemed necessary by the authors for the purpose of this study. However, it is important to note that the non-systematic nature of the search is a limitation as it is a potential source of bias and is not as transparent or reproducible as a structured systematic review that focuses on published peer-reviewed literature from scientific databases [271,272].

Stakeholders and policymakers are under pressure to make decisions on climate change based on existing knowledge. In some cases, a lack of information may result in a potential impact being omitted, but this is also a barrier to future planning of the sector. In this study, for possible links where there was a lack of clear evidence, the 'Potential' category was used to highlight a need to increase our understanding. More research is clearly required into many aspects, but at the same time, lack of information that leads to delayed adaptation planning, could leave the industry vulnerable. In that case, the industry or the policymakers may still develop and implement adaptation responses rather than wait until it is too late to act. However, adaptation responses selected based on insufficient information could have unintended consequences or lead to maladaptation [25]. Hallegatte [273] suggested that in the case of uncertainty, there may still be benefits in implementing adaptation responses to increase robustness of the system. These could be adaptation responses that are reversible or flexible, or responses that would have benefits even in the absence of climate change [273]. Some of the adaptation responses identified in this study would fall into this category and may already be in use.

The results show that most impacts may be affected by, or result from, multiple stressors, for which there are many knowledge gaps about their interactions. Multiple stressors, which may also include non-climate related factors (and other impacts), add complications, as they could have antagonistic or synergistic effects, and the nature of the impact and response of the fish may be different than that of a single stressor [13,142]. This was another reason that this study only considered if there was a link between climate stressors and impacts and did not assign risk scores. The use of studies in predicting the behavioural and physiological responses to extremes in the wild or farm environment is limited, as the range of responses available to fish and complex interactions of competing environmental influences cannot be fully replicated in the laboratory and there must be caution on interpretation of results from experimental and tank trials [274–276].There is a need for more research that integrates farm-level monitoring data and fieldwork with the results of controlled tank trials and laboratory experiments, to better inform predictive computer modelling and impact assessments.

This work shows that each stage of salmon production will be impacted by climate change, albeit in different ways. Industry, researchers, government, regulators, and policymakers all have a role to play in supporting the future development and management of salmon aquaculture, highlighting the importance of involving all stakeholders in impact analysis, risk assessments and adaptation plans to ensure the most appropriate responses are available when needed [277]. Co-operation and communication across stakeholder groups are key to an effective response to future challenges.

Two transformative adaptation responses were not included in this study: diversification and genetic modification. Diversification of the aquaculture industry and farming of new species has been suggested as a potential option for adaptation [278], but diversifying production through additional or new species can be a challenge, especially for a country like Norway where production and associated infrastructure is dominated by a single species. Genetically modified or transgenic salmon would be another dramatic change for the Norwegian industry, as salmon could be engineered to have specific traits, but would need to gain public acceptance and regulatory approval before use [279]. These transformative responses were not included as they would require a considerable change in the structure of the Norwegian aquaculture sector and would be a move away from salmon production, at least as it is recognised now. Diversification of species is however suggested as one of the main strategies when it comes to adapting to climate change in the aquaculture sector [278]. To prepare Norway for this transition, a selection of species with commercial potential should be identified based on their environmental preferences, and a framework, like the one presented here, developed to identify specific climate stressors and impacts, as well as possible adaptation responses.

A specific socioeconomic category was not explicitly included in this study, but aspects are partially integrated within many of the impacts and adaptation responses. Socioeconomic factors are another example of real-world complexities influencing future salmon aquaculture in Norway [280]. It can be difficult to isolate the effects of climate change on socioeconomics, and vice-versa, as socioeconomics are influenced by farm or company practices and national and international policies and interventions [20]. For example, many of the impacts outlined in the production stages would affect Norwegian salmon economic productivity, which has a major role in determining supply of salmon, and any changes could influence sector scale, distribution, value-adding and employment. At another level, Norwegian salmon farming is part of the global food system [20,280], where all sectors will be influenced by climate change, and competition with other salmon producing countries or other food commodities could alter the relative productivity of the Norwegian salmon farming sector and thus influence the overall shape of industry in Norway. Some of the difficulties in analysing socio-economic factors is the challenge in predicting future human behaviour, societal values, and political agendas. This is beyond the scope of this work, but this study provides a starting point for discussions with a range of stakeholders across all aspects of the Norwegian salmon aquaculture industry and beyond. Such discussions can facilitate better understanding of the complexities and knowledge-sharing across a range of experiences and topics, allowing identification of research needs and supporting development of improved strategies that represent the real-world challenges faced by the sector.

5. Conclusions

This research has shown some of the real-world complexities of the impacts of climate change for aquaculture production. A knowledge base such as the one presented here, can provide an overview of how different aspects of production are connected as well as potential links between climate stressors, impacts and adaptation responses. Knowledge gaps must be emphasised rather than ignored to highlight uncertainties and areas that need further research. Likewise, the knowledge base constructed in this study, and provided in the S1 Appendix, should not be seen as an end-point and it can be built upon and improved by other studies or stakeholders as more knowledge and data become available. A regular stock-take of information will facilitate improved knowledge transfer and provide all stakeholders with the most up-to-date information and will enable a more effective response to future challenges with the aim of maintaining or increasing aquaculture production sustainably. Whilst this study has focused on salmon aquaculture in Norway, the work is also relevant for a broader audience. The approach can be used in other countries for different species and types of aquaculture, and it can also be used for other industries and activities such as fisheries or other forms of food production. The Excel provided in S1 Appendix can serve as a template that can be adapted and applied elsewhere.

An understanding of the real-world complexities supports more robust analysis of existing and potential impacts affecting industry and wider supply chain. Decisions can then be made on the most appropriate adaptation responses as well as consideration of the consequences of action or inaction. Ultimately, more informed assessments that focus on particular parts of the aquaculture sector, such as Norwegian salmon aquaculture, will strengthen the sector as a whole and allow aquaculture to fulfil its increasingly important role in 21st Century food production.

Supporting information

S1 Appendix. Norwegian salmon aquaculture knowledge base.
(XLSX)

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