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Aquaculture Adaptation Framework for Climate Change (Aqua-Adapt)

A tool to support the development and implementation of strategies to improve aquaculture's resilience to climate change

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A tool to support the development and implementation of strategies to improve aquaculture's resilience to climate change

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Preparation of this document

The work presented here summarizes the development process and the content of the Aquaculture Adaptation Framework for Climate Change (Aqua-Adapt). In collaboration with experts from the Interdisciplinary Center for Aquaculture Research (INCAR) of the University of Concepcion, Chile, the Food and Agriculture Organization of the United Nations (FAO) presents Aqua-Adapt as a valuable tool to guide countries and relevant stakeholders in developing and implementing strategies to improve aquaculture resilience to climate change.

This document was prepared by a group of experts. After proposing a preliminary version of Aqua-Adapt, it was submitted to a global team of experts for review, and their feedback was incorporated into the final version. After that, two case studies on salmon and mussel farming in Chile were examined through the preliminary implementation of Aqua-Adapt.

The document is divided into three chapters. These consider i) a literature review of the status, issues, and challenges for aquaculture adaptation under climate change; ii) the process to develop and implement Aqua-Adapt; and iii) the results of the application of Aqua-Adapt to two case studies in Chilean aquaculture. Additionally, Annex 1, contain a summary of Aqua-Adapt guiding its application as a printable version to facilitate its use.

This document provides information and guidance to help identify the main climate change risks aquaculture faces, and possible solutions for dealing with them.

Abstract

Aquaculture's vulnerability to climate change urgently requires practical adaptation strategies. To strengthen the sector's resilience, countries should develop strategies that include actions from various stakeholders from the field (species, farms, farming systems, farming communities, research and innovation systems, etc.) to the governance level. Findings from previous studies indicate the need for more climate-resilient measures and guidance on recognizing and classifying technologies, innovations, and solutions that can decrease the risk of – and increase resilience to – climate change. Thus, the current initiative developed an Aquaculture Adaptation Framework for Climate Change (Aqua-Adapt) as a tool to support the development and implementation of strategies to improve aquaculture's resilience to climate change.

FAO developed Aqua-Adapt in partnership with researchers from Interdisciplinary Center for Aquaculture Research (INCAR), including a consultative process with international experts from different regions. The deliberations and recommendations of these experts were incorporated into the final version of Aqua-Adapt. To finalize the development of Aqua-Adapt, two case studies, one on salmon farming and the other on mussels, were implemented. This allowed adjustments and a greater understanding of potential technologies to make them more resilient.

Aqua-Adapt was developed using definitions based on the fifth and sixth Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, which establish that the adaptation process should focus on risk reduction while increasing opportunities.

Aqua-Adapt proposes a six-step process that must incorporate the participation of relevant stakeholders and access to the best available information, on the development of an adaptation strategy. The first step is to establish the unit of adaptation which may range from individual farmers to the minimum geographical and/or geopolitical unit of adaptation. The unit of adaptation includes the farmed species and associated socio-ecological systems at appropriate spatial scales. The second step is to identify and chose the most appropriate climate projection pathways and models. The third step is to perform a risk and vulnerability assessment on the defined unit. This crucial task involves predicting and identifying the most significant hazards to guide adaptation actions and timing. This step must be fed with the best available information, including climate projections and chosen scenarios and time scales. The fourth step is to design an adaptation work plan to reduce the identified exposure and sensitivity and increase adaptive capacity in the adaptation unit. This includes elaborating a timescale for implementation (actions required in the short-, medium- and long-term to improve resilience in the adaptation unit) and choosing the best adaptation options considering the effectiveness of measures, costs, and technical difficulties. Also, it must consider the co-benefits of adaptation measures, the potential for maladaptation, and human and financial resources. The fifth step involves implementing the strategy following the work plan. The sixth implicate conducting ongoing monitoring and evaluation to enhance the efficiency and effectiveness of the implemented measures, costs, and/or technical difficulties.

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Acknowledgements

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Abbreviations

AM	antimicrobials
ARClim	Climate Risk Atlas of Chile
AC	adaptive capacity
C-E	cost-effectiveness
EAA	ecosystem approach to aquaculture
E	exposure
Eff	effectiveness
FAO	Food and Agriculture Organization of the United Nations
FCR	feed conversion ratio
FW&B	freshwater and brackish ecosystems
GHG	greenhouse gases
GSA	guidelines for sustainable aquaculture
H	hazard
HAB	harmful algal blooms
INCAR	Interdisciplinary Center for Aquaculture Research
IPCC	Intergovernmental Panel on Climate Change
IMTA	integrated multitrophic aquaculture
IA	integrated aquaculture
M	marine
MMA	Chilean Ministry of Environment
NAP	national adaptation plans
R	risk
RAS	recirculating aquaculture systems
R&D	research and development
RCP	representative concentration pathways
S	sensitivity
Sernapesca	National Fisheries and Aquaculture Service of Chile
SFA	salmon farming concession areas
SSP	shared socioeconomic pathways
UNFCCC	United Nations Framework Convention on Climate Change
Va	vulnerability
WGII	IPCC AR6's Working Group II

CHAPTER 1
Status, issues, and challenges for aquaculture adaptation under climate change: literature review

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I. INTRODUCTION

The implications of climate change on aquaculture's productivity and production capacity are being increasingly documented (De Silva and Soto, 2009; Reid *et al.,* 2019; Froelich *et al.,* 2022). This reinforces the need to consider strategies to improve aquaculture's resilience to climate change, including actions from various stakeholders from the field (farm, species, systems, etc.) to the governance level.

Aquaculture's vulnerability to climate change urgently requires practical adaptation strategies. The sector's vulnerability demands the strengthening of governance for adaptation, including the development and adoption of technologies and strategies that increase the adaptive capacity of production systems (Soto *et al.,* 2018).

Good governance is essential for implementing successful aquaculture adaptation strategies, and FAO and other organizations, including the Intergovernmental Panel on Climate Change (IPCC, 2023), have produced guidance to help improve it (FAO, 2022). FAO has published guidance on how countries can incorporate fisheries and aquaculture into their National Adaptation Plans (NAPs) and Nationally Determined Contributions (NDCs) (Brugère and De Young, 2020; Stanford Center for Ocean Solutions *et al.,* 2024), along with several other manuals and tools to increase the sector's resilience in the face of climate change. In addition, specific guidance for aquaculture tailored to the particular needs of the sector – which is often more similar to agriculture than to fisheries – is readily available (e.g. see Norambuena *et al*., 2024; Stanford Center for Ocean Solutions *et al.,* 2024).

The findings from previous FAO studies indicate the need for more resilient actions and guidance on adaptation, including how to recognize and classify the various technologies and solutions which can help achieve it. Specifically, more detailed guidance is required on practical frameworks to improve the adaptive capacity of aquaculture, and on how to design adaptation initiatives.

II. METHODOLOGICAL APPROACH

The search engine Scopus (www.scopus.com) was used, as well as Google Scholar to add FAO articles that did not appear in the Scopus search; the search terms used were "climate change" + "aquaculture" + "species" in the period 2000 to the first half of 2023. Other aquaculture-related terms were used in the literature search (e.g. fish farming, shrimp farming).

For each publication, the following information was obtained:

- species or species group;
- main forcing factors and hazards including harmful changes in water temperature, extreme climate-related events, oxygen reduction, increase of harmful algal blooms (HABs), ocean acidification, harmful changes of salinity, sea level rise, pests and

diseases, and "ALL" if more than three factors are included. The classification of main hazards for aquaculture followed De Silva and Soto (2009);
- environment (marine, brackish, freshwater, and "ALL" if the previous three are included); and
- regions (continents and regions).

Then an attempt was made to classify, and group published documents according to the **main emphasis or focus under the following categories**:
- **BRAd** – Basic research on climate change potential impacts on aquaculture and general implications for adaptation addressing physiological aspects, species, genetics, etc., including modelling and projections. This includes reviews of published information on climate change impacts on aquaculture and identified adaptation pathways.
- **RVAd** – Risk and/or vulnerability assessments applied to specific geographical areas (could also be of a global nature) and/or aquaculture systems or species involving general adaptation measures.
- **RVMP** – Risk and/or vulnerability assessments applied to areas and/or aquaculture systems involving adaptation measures that specifically consider better management of production.

The **BRAd** category includes literature describing the process for adaptation, which involves gathering information to identify anticipated climate change impacts and general adaptation approaches. While **RVAd** and **RVMP** categories refer to articles on risk and/or vulnerability assessments, the latter includes articles that identify specific adaptation measures to reduce identified risks. Within the **RVAd** and **RVMP** categories, the authors also attempted to identify and characterize risk assessment approaches.

In this review, the authors use the concept of "**adaptation measures**" to encompass any measures designed to reduce climate change-related risks and impacts. Some publications offer general descriptions of "**adaptation pathways or approaches"** to denote processes towards adaptation, while others describe very specific tools and options such as integrated aquaculture (IA), recirculating aquaculture systems (RAS), aquaculture diversification, etc. (Ahmed and Glaser, 2016; Galappaththi *et al.*, 2020). Therefore, the classification of publications under the three categories defined above has a degree of subjectivity. This was also the case when attempting to identify risk and vulnerability assessments.

III. MAIN FINDINGS

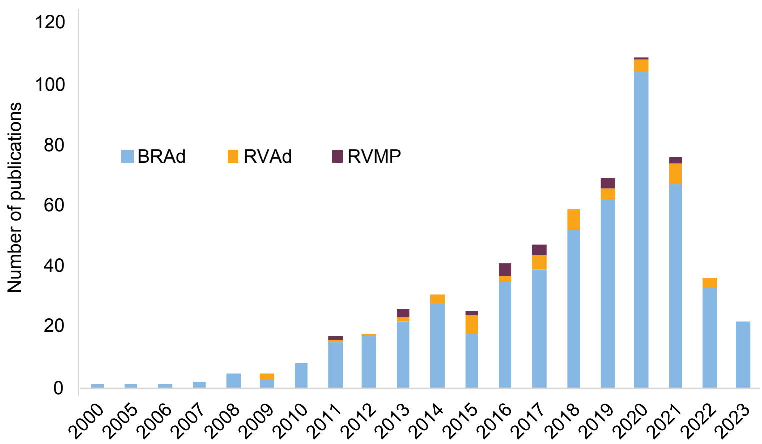
The authors identified 598 publications (dating from 2000 to the first half of 2023) that addressed direct or indirect climate change hazards for and impacts on aquaculture, and, or addressed risk and vulnerability, and, or provided some information on adaptation. All publications identified by Scopus were in English, while a few FAO documents were in Spanish.

i. Publications trends and focus

The number of publications addressing climate change implications for aquaculture increased steadily from 2000 to 2020 (Figure 1); this pattern has already been noted by Dabbadie *et al.*, (2018). The sharp decrease after 2020 is probably a result of the global COVID-19 pandemic.

About 90 percent of the publications identified in the present review address climate change hazards, potential impacts on aquaculture species and systems, general risk and vulnerability implications, and various adaptation approaches and measures. However, only in about 10 percent of the publications there is a specific description of some

FIGURE 1
Number of publications per year addressing direct and indirect effects of climate change on aquaculture, organized by focus

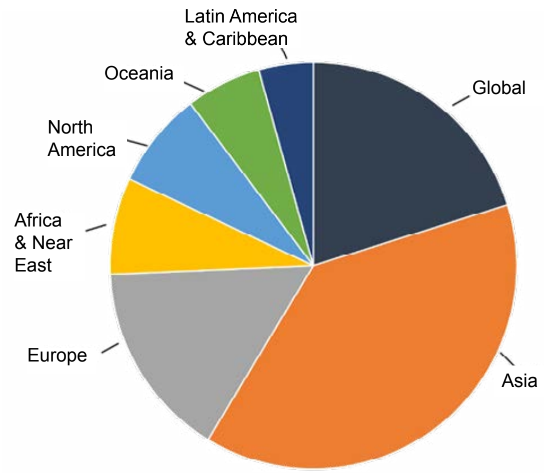


Note: BRAd = Basic research on climate change potential impacts on aquaculture and general implications for adaptation addressing physiological aspects, species, genetics, etc., including modelling and projections; RVAd = risk and/or vulnerability assessments applied to specific geographical areas (could also be of a global nature) and/or aquaculture systems or species involving an adaptation measure; and RVMP = risk and or vulnerability assessments applied to areas and/or aquaculture systems involving adaptation measures that consider better management of production. Data for 2023 covers only publications released during the first half of the year.

form of risk[1] and/or vulnerability assessment, according to the concepts described by the IPCC (IPCC, 2014; Cooley *et al.*, 2022) and by other authors including in FAO publications (Handisyde, Telfer and Ross, 2017; Brugère and De Young, 2015; Bueno and Soto, 2017; Soto *et al.*, 2018; Comte, 2021) (Figure 1).

While 20 percent of the publications are global, those that are generated by specific regions (Figure 2) are dominated by Asia (48 percent). This could be considered an underrepresentation, since this region is responsible for nearly 90 percent of global aquaculture production (FAO, 2024).

FIGURE 2
Distribution of publications by region

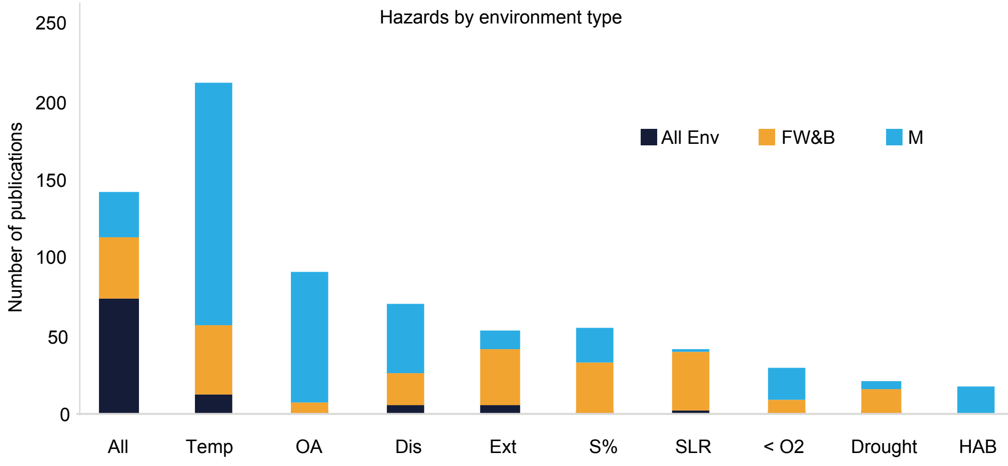


ii. Main hazards for aquaculture at the global level

Hazards and chain of events impacting aquaculture are described in several publications (De Silva and Soto, 2009; Dabbadie *et al.*, 2018; Froehlich *et al.*, 2022) and they mostly group in six categories described in Figure 3. In all the cases one or more hazard caused direct or indirect loses to aquaculture (increase mortality of farmed

[1] Risk is a function of hazard, exposure and vulnerability (**FAO.** 2016. Climate change implications for fisheries and aquaculture: Summary of the findings of the Intergovernmental Panel on Climate Change Fifth Assessment Report, by Anika Seggel and Cassandra De Young. FAO Fisheries and Aquaculture Circular No. 1122. Rome, Italy. https://openknowledge.fao.org/server/api/core/bitstreams/ccddd8cf-c3dc-4750-a16a-7a00db334908/content)

FIGURE 3
Number of publications by environment, including indicated hazard or main cause of impacts



Note: All = publications including all potential factors; Temp = including temperature as a main forcing factor; OA = ocean acidification; Dis = diseases and/or pests; Ext = extreme weather events; S% = changes in salinity; SLR = sea level rise; <O2 = oxygen reduction; Drought = drought; HAB = harmful algal blooms. Many publications include more than one factor. The colours in the bars indicate the type of environment where the information was identified: All Env = all types of environments; FW&B = freshwater and brackish; and M = marine environments.

individuals, reduced growth and performance, infrastructure loss, etc.). Regarding the type of environment where aquaculture takes place, about 20 percent of the publications cover climate change impacts in all environments; however, publications and information that identify specific type of farming environment are most common for marine aquaculture (62 percent). Thus, inland aquaculture – which accounts for more than 60 percent of global production – is underrepresented. This is probably due to the fact that there is more research and monitoring in the more developed regions of the world where mariculture takes place, while inland aquaculture occurs mostly in less developed regions where scientific literature is less abundant. The identified hazards at the global level reflect this pattern, with ocean acidification appearing to be the second-most important factor after changes in temperature (Figure 3) – whereas the most vulnerable countries at the global level must adapt to factors such as extreme weather events, salinization and sea level rise (Handisyde, Telfer and Ross, 2017; Dabbadie *et al.*, 2018). Diseases and pests associated with climate change seem to be an important factor for both marine and inland aquaculture.

When publications are organized by main taxa, the same pattern is recognized. Thus, there is a greater focus on farmed marine molluscs than on farmed inland fish (Figure 4).

Therefore, the analysis of the literature suggests that more research and communication efforts are needed to understand the implications of climate change (impacts, risks, adaptive capacity) for farmed inland fish, which are very relevant for food security in less developed countries, and for seaweed, which also plays a key role in climate change mitigation. This pattern has also been observed by other recent reviews (Froelich *et al.*, 2022).

Risk assessment approaches

Of all the publications reviewed, only a small proportion addressed the assessment of risk and/or vulnerability by describing some of their components (Figure 5). It is important to notice that even though the largest proportion of studies are from Asia,

FIGURE 4
Number of publications by main farmed taxa, (focus of publication) including all farmed groups and environments (ALL TAXA), molluscs (MOLLUSC), fish (FISH), crustaceans (CRUST), seaweed (SEAWEED), and other marine species (OTHER_M) such as echinoderms, tunicates etc., organized by the following categories: freshwater and brackish ecosystems (FW&B), marine ecosystems (M) and publications that do not differentiate by environment types (ALL)

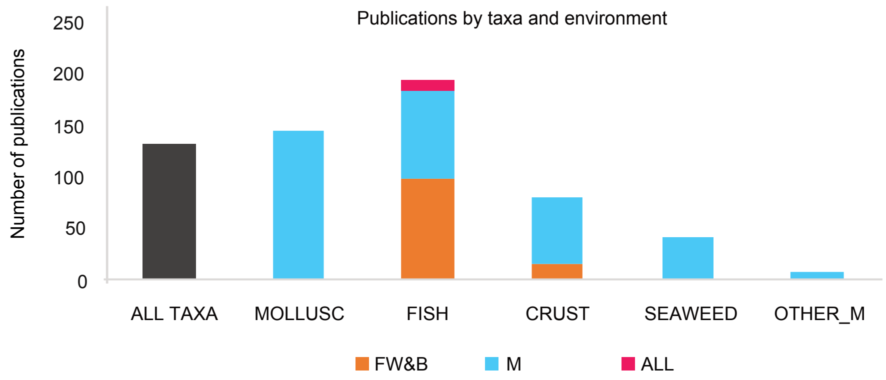
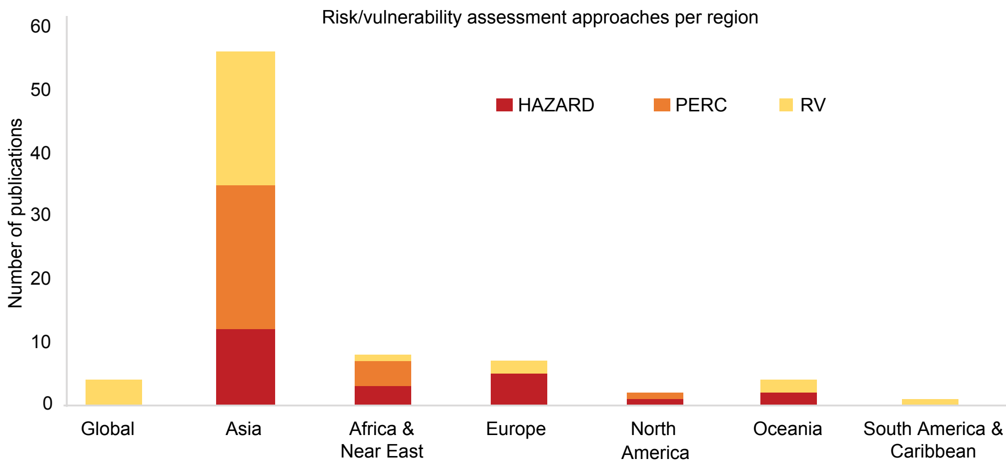


FIGURE 5
Types of risk/vulnerability approaches per region



Note: HAZARD = focusing mainly on the identification of hazards; PERC = estimated through perceptions of stakeholders; RV = performed more formal risk assessment by identifying and estimating risk components, including hazards.

this proportion does not account for the highest representation of that region for global production. Three types of assessments were identified:

- **Identification of the hazards.** In some publication, there was a clear identification of hazards through field evaluation, with modelling of climatic projections for given species or farming systems or for a specific geographical area, followed by projections of impacts and suggestions for mitigation and adaptation approaches.
- **Assessment through stakeholders' perceptions.** A common type of assessment, especially in some countries in Asia and Africa, involved the evaluation of farmers' and other stakeholders' perceptions of hazards and impacts, often also involving the identification of practical adaptation measures (Figure 5). Most of these cases are small-scale aquaculture also indicating that they are more vulnerable (Lebel

et al., 2015). Only in a very few cases was there an assessment of the effectiveness of the adaptation measures.

- **Risk and /or vulnerability assessments involving adaptation.** In fewer cases, there were more traditional risk and/or vulnerability assessments that identified risk components, including hazards, exposure, sensitivity, and **adaptive capacity**. For the latter, the authors were also interested in identifying those cases where better management practices were identified as important.

IV. REVIEWS AND GUIDANCE ON AQUACULTURE ADAPTATION

i. FAO tools and guidance: the governance of adaptation

A total of 50 FAO publications were identified as Table 1 providing reviews of hazards, impacts, vulnerability aspects and recommendations for adaptation (Table 1). Most of these are of a global nature and cover all taxa and environments. Also, a large proportion of the publications cover both fisheries and aquaculture. Many address climate change impacts and adaptation options in a general way.

FAO has produced two extensive reviews on the status of fisheries and aquaculture under climate change (Cochrane *et al.*, 2009; Barange *et al.*, 2018; see Table 1). These cover different regions, types of impacts and some recommendations for adaptation, including a toolbox (Poulain, Himes-Cornell and Shelton, 2018) which provides an initial framework and strategy to address adaptation in fisheries and aquaculture. The first global review of fisheries and aquaculture under climate change (Cochrane *et al.*, 2009) included a specific chapter on aquaculture (De Silva and Soto, 2009) which provided an initial analysis of the impacts on the sector. The second review (Barange *et al.*, 2018) includes four chapters dedicated to aquaculture (FTP 627, Chapters 20 to 24). More recently, FAO publications have focused on the need to include aquaculture in NAPs and NDCs to address climate change (Brugère and De Young, 2020; Stanford Center for Ocean Solutions *et al.*, 2024). While several of these FAO publications do address adaptation approaches for aquaculture, in the global literature reviewed here <u>specific adaptation measures and approaches for the sector have not yet been adequately addressed</u>. This is important, considering the global significance of aquaculture and given the fact that it is quite different from fisheries. However some publications provide relevant information and guidance (Table 2), and this is also a focus in the development of case studies to be described in Chapter 3.

TABLE 1
FAO publications and documents addressing climate change impacts on aquaculture and/or both fisheries and aquaculture

Authors	Year	Scope
Focus: Climate change impacts and adaptation		
Barange *et al.*	2018	Global
Dabbadie *et al.*	2018	Global
Bueno and Soto	2017	Global
FAO	2017a	Global
FAO	2017b	Africa & Near East
FAO	2016a,b	Global
FAO	2016c	Latin America & Caribbean
Seggel and De Young	2016	Global
Shelton	2014	Global
Soto and Quiñones	2013	Latin America & Caribbean
Curtis *et al.*	2011	Africa & Near East
FAO	2011	Asia

TABLE 1 (CONTINUED)

Authors	Year	Scope
Focus: Climate change impacts and adaptation		
Sriskanthan and Funge-Smith	2011	Asia
Cochrane *et al.*	2009	Global
De Silva and Soto	2009	Global
FAO	2008	Global
Focus: Climate change impacts and biosecurity		
Bondad-Reantaso, Garrido-Gamarro and McGladdery	2018	Global
Focus: Impacts of crises such as climate change		
FAO	2018	Global
Focus: Climate change emergency response		
McConney *et al.*	2015	Latin America & Caribbean
Cattermoul, Brown and Poulain	2014	Global
Davies *et al.*	2014	Africa & Near East
FAO	2014a	Africa & Near East
FAO	2014b	Africa & Near East
Brown and Poulain	2013	Global
Focus: Climate change impacts and interactions with other sectors		
Beveridge *et al.*	2018	Global
Gregory, Funge-Smith and Baumgartner	2018	Global
Ottaviani, De Young and Tsuji	2017	Asia/Africa & Near East
Ottaviani, De Young and Tsuji	2016	Global
Focus: Adaptation toolbox		
Poulain, Himes-Cornell and Shelton (Chapter 25 in FTP 627)	2018	Global
Focus: National adaptation plans (NAPs), policies and strategies		
Norambuena *et al.*	2024	Global
Brugère and De Young	2020	Global
Vadacchino, De Young and Brown	2011	Global
FAO	2010	Global
Focus: Risk/vulnerability and adaptation		
Thein *et al.*	2019	Asia
Soto *et al.*	2018	Global
FAO	2016a,b	Global
Brugère and De Young	2015	Global
Brugère and De Young	2013	Africa & Near East
Barsley, De Young and Brugère	2013	Global
Johnson, Bell and De Young	2013	Global
Focus: Economics of adaptation		
Watkiss, Ventura and Poulain	2019	Global
Cai *et al.*	2018	Global
Focus: Diversification for adaptation		
Harvey *et al.*	2017	Global
Focus: Environmental monitoring and early warning		
Virapat, Wilkinson and Soto	2017	Asia
Bravo Moreno, Orozco Montiel and Soto	2016	Latin America & Caribbean
Focus: Spatial planning		
Aguilar-Manjarrez, Wickliffe and Dean	2018	Global
Aguilar-Manjarrez, Soto and Brummet	2017	Global

Source: Author´s own elaboration and using information from **FAO**. 2019. FAO’s work on climate change – Fisheries & aquaculture 2019. Rome, FAO. 61 pp. www.fao.org/3/ca7166en/ca7166en.pdf

V. OTHER RELEVANT PUBLICATIONS

Within the literature publications reviewed, the authors identified at least 60 (Scopus) published documents that provide relevant information and guidance.

Table 2 and Table 3 show a number of publications that provide useful information on the adaptation process and specific adaptation options, respectively. In particular, Table 2 shows publications which do not include direct risk and/or vulnerability assessments, but that contribute with new research, analysis of information, reviews and syntheses of climate change adaptation approaches in aquaculture. Table 3 shows studies that involve some form of risk and/or vulnerability assessment and provide recommendations for specific adaptation approaches.

Publications include governance approaches to address specific hazards such as ocean acidification (Greenhill, Kenter and Dannevig, 2020), and descriptions of strategic approaches such as that developed by the European Union for fisheries and aquaculture (Pham *et al*., 2020; Pham *et al*., 2021) which develops a risk and opportunity framework.

Relevant publications within this group (Table 2) include systematic reviews of adaptation practices (Ahmed, Thompson and Glaser, 2019; Galappaththi *et al*., 2020; Abu Samah *et al*., 2021; Lebel *et al*., 2021a). Some publications underscore the fact that identifying specific hazards is very important for adaptation to succeed (Abisha *et al*., 2022). Several publications also address specific adaptation options, such as genetic improvement of fish and other farmed organisms to increase salinity resistance, under sea level rise (Dao Minh *et al*., 2022). Improving biosecurity appears important for addressing climate change-induced diseases (Ferreira *et al*., 2021; Reverter *et al*., 2020). Livelihood diversification, including diversified aquaculture and integrated multitrophic aquaculture (IMTA), frequently appears as an adaptation approach (Tran *et al*., 2020; Basu and Roy, 2021; Bernzen *et al*., 2023). However, the success of such approaches does not seem to be guaranteed; while in many cases it is not clear if the different species in an IMTA or polyculture system respond differently to the same hazard.

TABLE 2
Examples of published cases of adaptation approaches that focus on reducing known (or estimated) risks for aquaculture

Authors	Adaptation approaches	Country	Aquaculture species/system
Biswas and Mallick, 2021	Livelihood diversification	Bangladesh	Shrimp
Poelma *et al*., 2021	Integrated farming for adaptation	Viet Nam	Shrimp
Soto *et al*., 2021	Reduce production in high-risk areas	Chile	Salmon
Akter and Ahmed, 2021	Change cropping seasons and species	Bangladesh	Shrimp, crab
Lebel *et al*., 2015, 2018b; Lebel, Lebel and Lebel, 2016	No-regret (e.g. harvest fish early, aeration) and low-regret strategies (e.g. adjust feeding)	Thailand	Freshwater fish
Asiedu, Adetola and Odame Kissi, 2017	Building boreholes, siting farms close to water bodies, adjusting fish stocking time	Ghana	Tilapia
Ahmed and Diana, 2016	Adaptation strategies according to risks (e.g. netting and fencing ponds, rainwater harvesting)	Bangladesh	Freshwater fish
Seekao and Pharino, 2016	Increase dike height around ponds	Thailand	Shrimp
Pimolrat *et al*., 2013	Manage feeding and harvesting	Thailand	Tilapia

Source: All references used are included under the Reference Section on page 12.

TABLE 3
Examples of short-term and mid-to-long-term adaptation options that may improve the overall resilience of the sector, directly involving farmers

Short-term immediate adaptation options (better management)		Mid-to-long-term adaptation options (future benefit strategies)	
No regret*/will provide benefits anyway	**Low regret/some additional costs involved**	**Low regret/some additional costs involved**	**Substantial costs, government and technical assistance usually required**
Provide supplementary aeration as appropriate (weather-related stress/ variations)	Shift stocking dates and adjust stocking density	Protect and improve surrounding landscape and vegetation cover (e.g. mangrove restoration)	Strategic spatial planning to reduce risks Strategic environmental and climate monitoring and early warning systems
Harvest fish early to reduce losses (extreme weather events, HAB, etc.)	Switch available species, change species combination	Perform local species selection to improve breed	Aquaculture diversification Develop new farming strains and species that are more resistant to climate change
		IMTA implementation	
Intelligent water management	Use groundwater to pump ponds	Implement new farming technologies, reduce water use	Implement RAS systems
Monitor water conditions and fish behaviour especially during high-stress periods (high temperatures, low oxygen, HABs, etc.)	Adapt/build resilient infrastructure, dikes and ponds Strengthen cages	Resource certified climate-proof farming systems	
Improved biosecurity	Consider vaccines, fish health enhancers, etc.	Improved provision of services for aquaculture (e.g. veterinary services, mortality handling, harvest, etc.)	
Adopt good feeding management practices to reduce fish stress (e.g. feeding early to avoid storms, excessive heat)			

* No regret here refers to the fact that if costs are involved, they will likely generate benefits regarding other purposes or outcomes.

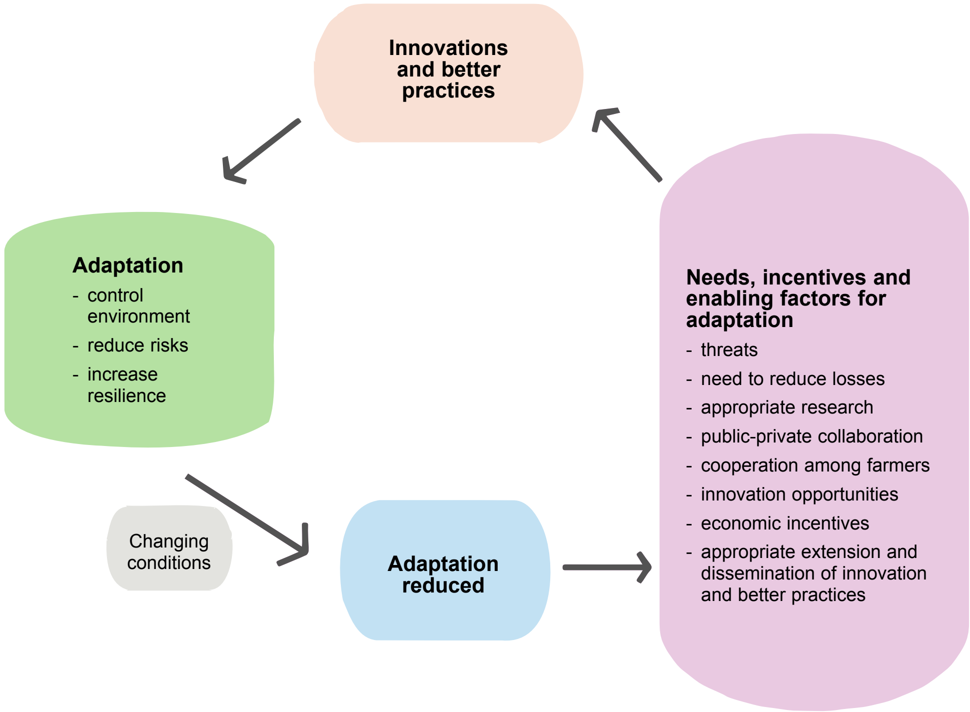
Note: HAB = harmful algal bloom; RAS = recirculating aquaculture systems; IMTA = integrated multitrophic aquaculture.

Source: See references.

Fewer publications used the stepwise approach of identifying hazards, performing a risk and/or vulnerability assessment, and then identifying the best adaptation options; within those, however, there are some very useful findings to feed into an adaptation framework. In most cases, publications describe the specific 'unit of adaptation,' namely a geographical area and/or an aquaculture system. Most of these are in Asia (Pimolrat *et al.*, 2013; Ahmed and Glaser, 2016; Nguyen *et al.*, 2016; Lebel *et al.*, 2016; 2018a,b; 2021a; Macusi *et al.*, 2021, 2022), among others, with a few in Africa (Onyeneke *et al.*, 2020; Adekola *et al.*, 2022) and Latin America (Soto *et al.*, 2019; Matoju *et al.*, 2022., Engelhard *et al.*, 2022).

Most publications however deal with practical adaptation options in inland systems, and most of these were identified by instruments assessing stakeholders' perceptions.

FIGURE 6
Process generating innovation and adaptation



Source: Modified from **Lebel, L., Navy, H., Jutagate, T., Akester, M.J., Sturm, L., Lebel, P. and Lebel, B.** 2021. Innovation, Practice, and Adaptation to Climate in the Aquaculture Sector. *Reviews in Fisheries Science & Aquaculture*, 29 (4): 721–738 https://doi.org/10.1080/23308249.2020.1869695

Publications dealing with aquaculture in the marine environment emphasize the process of assessing risk and, or vulnerability, and the importance of identifying hazards (Table 3; Hobday *et al*., 2016; Handisyde, Telfer and Ross, 2017; Soto *et al*., 2019; Falconer *et al*., 2020; Adekola, Gatonye and Orina, 2022). Other publications refer to aquaculture as an adaptation option (Dam *et al*., 2021)

i. Technologies, innovative systems and solutions in aquaculture that improve resilience to climate change

Several authors describe a stepwise process towards adaptation and the types of possible actions; for example, Lebel *et al*. (2018a, b) describe five strategy types based on patterns of risk-reduction, and their benefits and costs over time.

Lebel *et al*. (2021a) describe adaptation actions of three types – material, procedural and informational – and describe several mechanisms to develop them, while noting that innovation is essential (Figure 6). However, this leaves out specific actions for better management which are the first step towards adaptation and do not necessarily require innovation, but a better understanding of how to improve aquaculture management.

ii. Evidence of successful adaptation approaches

Most evidence on adaptation approaches in the field comes from the assessment of stakeholders' perceptions of climate change risks and how they cope with them. The largest numbers of studies come from Bangladesh, Viet Nam and Thailand, with a few from the Philippines and India, and a couple from Africa (Table 2).

Broadly speaking, there is not enough evidence of successful adaptation in terms of objective evaluation of reduced losses or increased profitability. However, there are a few cases where models are developed to forecast changes in profitability, good case studies are described by Lebel *et al*. (2018a,b).

Clearly, governments and the private sector need to evaluate different adaptation alternatives in terms of their effectiveness, costs, and additional benefits (see also the case studies in Chapter 3).

VI. INCLUSION OF AQUACULTURE IN NATIONAL ADAPTATION PLANS, AND INSTITUTIONAL AND GOVERNANCE NEEDS

An essential way of stimulating and uniting efforts towards a strategy for adapting aquaculture to climate change is to provide guidance for its inclusion in National Adaptation Plans (NAPs). NAPs allow the identification of medium- and long-term adaptation needs, and the development and implementation of strategies and programmes to address them. NAPs should include all development sectors and should ensure the integration of individual adaptation approaches, avoiding maladaptation[2] or negative interference between sectors' adaptation options.

The process to formulate and implement NAPs was formally established at the 16th Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) in 2010 under the Cancun Adaptation Framework (UNFCCC COP Decision 1/CP.16, LEG, 2012). It is, therefore, essential to integrate aquaculture into NAPs, and it is also necessary to develop specific strategies, and adaptation plans for the sector. Brugère and De Young (2020) provide supplementary guidelines for including fisheries and aquaculture in NAPs.

The inclusion of aquaculture in NAPs is extremely relevant, especially when aquaculture shares land and water space and resources (e.g. water, feed ingredients) with other sectors, such as fisheries, agriculture, energy, and urban development. Brugère and De Young (2020) recommend a process and steps for NAPs, which can also be applied to address adaptation at subnational scale (Table 4). These authors use a checklist to describe the process for enhancing the adaptation of aquaculture to climate change at the national level to improve a NAP, including information and guidance from available publications (mostly produced by FAO).

TABLE 4
Main steps for including aquaculture in the NAP, and for developing an aquaculture-specific adaptation plan

A. Assess institutional structure and capacity and address gaps	A1 – Assessment of aquaculture institutional and individual capacity to participate in NAP development and implementation. A2 – Assessment of prior and current engagement of the aquaculture sector in climate change adaptation processes. A3 – Ensuring proper inter-institutional and intra-institutional coordination to facilitate the effectiveness of adaptation measures.
B. Preparatory elements	B1 – Stock-taking of available information in support of the inclusion of aquaculture in the NAP. B2 – Analysing expected impacts of climate change on aquaculture. B3 – Assessing the risks and vulnerability to climate change of aquaculture systems and the people they support at appropriate levels. B4 – Synthesising and ranking aquaculture climate change risks, impacts and socioecological vulnerabilities to determine adaptation goals. B5 – Identifying and reviewing aquaculture adaptation options, and cost/benefit analysis.
C. Implementation strategies	C1 – Identifying policy mechanisms that support institutional and livelihood adaptation, risk reduction, and management for resilience. C2 – Integrating aquaculture adaptation options and supporting policy measures. C3 – Mobilizing funds and human resources for implementation. C4 – Feeding the contents of the aquaculture adaptation plan into the NAP and national aquaculture development policies.
D. Communicating, monitoring and reviewing	D1 – Disseminating and communicating information about climate change adaptation. D2 – Monitoring and evaluation. D3 – Improving the plan and its implementation.

Source: Adapted from **Brugère, C. and De Young, C.** 2020. *Addressing fisheries and aquaculture in National Adaptation Plans.* Supplement to the UNFCCC NAP Technical Guidelines. Rome, FAO. https://doi.org/10.4060/ca2215en

[2] As defined by IPCC, see definition in page 42.

Many countries have developed their NAPs, and in some cases aquaculture has been explicitly included in the plans (De Jesus-Ayson, 2019); yet, in most cases, the focus is still on agriculture and urban protection. In this regard, the capacity of the ministries responsible for aquaculture needs to be strengthened so that they can develop, implement and promote an enabling environment to facilitate the mainstreaming of climate change adaptation (e.g. UNFCC, 2022; Cubillos-Santander *et al.*, 2021).

Poulain, Himes-Cornell and Shelton (2018) provide a set of measures to address climate change adaptation in fisheries and aquaculture, and advocate for strengthening capacity in some specific areas. For aquaculture, these must include:

- the assets, including financing, technology, services, land and water space, that stakeholders can access when needed;
- flexibility to modify strategies regarding farming, species, systems, marketing, etc.;
- the capability to organize and act collectively; and
- continuous learning to recognize and respond to the effects of climate change.

According to the same authors, these domains are cross-cutting and need to be considered across three principal areas: institutions, livelihoods, and risk reduction and management for resilience. In the case of aquaculture, it is also important to consider the roles and responsibilities of the private sector at all production levels. The role of aquaculture in direct and indirect employment and job creation is an essential part of this equation (Bueno and Soto, 2017).

Recently FAO published the NDC-Fish guidelines providing a foundational framework for integrating aquatic foods into Nationally Determined Contributions (NDCs) and other climate strategies (Stanford Center for Ocean Solutions *et al.*, 2024). Designed for policymakers and stakeholders involved in formulating and implementing NDCs and broader climate strategies, these guidelines provide diverse entry points for harnessing aquatic foods to mitigate and adapt to climate change, including supporting climate-adaptive technologies and practices to increase resilience to climate change.

The inclusion of aquaculture within NAPs, however, has tended to be of a general nature both because the NAP process is new for most countries and because aquaculture is a relatively new sector compared to agriculture, and often not a priority compared with agriculture and fisheries. While, in practice, NAPs emphasize that improvements in governance are priority actions for climate change adaptation, the specific technical needs of aquaculture have not been well addressed.

The statement above is confirmed by the literature review. About 90 percent of the publications analysed for this review address climate change hazards, potential impacts on aquaculture species and systems, risk and vulnerability implications, and various adaptation approaches. However, **in only about 10 percent of the publications there is a description of some form of risk and/or vulnerability assessment, or specific actions to reduce risks.** Nevertheless, there are a few publications which summarize different types of actions to improve adaptation to climate change, which may increase the overall resilience of the sector.

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CHAPTER 2
An Aquaculture Adaptation Framework (Aqua-Adapt) to assess strategies for adapting aquaculture to climate change

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I. INTRODUCTION

Aquaculture is highly vulnerable to climate change, which has important implications for productivity. As a key sector, aquaculture needs to recognize its vulnerabilities and create strategies to foster resilience, in order to continue to contribute to food security and livelihoods. Existing solutions include technologies and better management approaches that increase the adaptive capacity of production systems to better deal with climate change as required.

Improving aquaculture's resilience to climate change is essential, considering the sector's current vulnerability that requires practical and urgent adaptation strategies, with actions at all stakeholder levels, from farm owners, workers, aquaculture communities, service providers, science and innovation institutions, etc. to those responsible for governance, including policy makers and implementers.

As presented in Chapter 1, there have been many advances in scientific studies and proposed governance strategies to improve aquaculture's adaptive capacity. Moreover, there is a need for the identification and development of technological solutions and innovations to increase the sector's resilience to climate change. While adaptation responses are becoming available, and innovation is progressing there is a need for guidance in the process to identify and choose adaptation options by countries and relevant stakeholders; thus, this chapter presents an Aquaculture Adaptation Framework for Climate Change (Aqua-Adapt) to contribute filling the gap. The aim of the framework is to support the development and implementation of strategies to improve aquaculture resilience to climate change, while taking into account the local, national or regional peculiarities.

Aqua-Adapt can also be understood as a tool to advance and increase aquaculture resilience and therefore the "tool concept" is often used in this document.

i. Aqua-Adapt and its development process

Aqua-Adapt was developed using concepts and definitions based on the 5th and 6th IPCC Assessment Reports and proposes an adaptation process that focuses on risk reduction while increasing development opportunities that may also arise from climate change (Figure 7). The framework is aligned with the ecosystem approach to aquaculture (EAA; FAO, 2010), and therefore the adaptation process and adaptation options should be developed under the following principles:

- Consider ecosystem functions and services (including biodiversity) with due attention to avoiding their degradation and building their resilience.
- Improve human well-being and equity for all relevant stakeholders.

- Consider other sectors, policies and goals, as appropriate, especially when sharing common resources such as water, space, farming inputs and outputs, etc.

These principles also align with the recently adopted Guidelines for Sustainable Aquaculture (FAO, 2025), as well as the Adaptation Policy Cycle as described in FAO Fisheries and Aquaculture Technical Paper No. 650 (Watkiss, Ventura and Poulain, 2019). In addition, the framework proposed here can be used when developing EAA management plans and/or aquaculture co-management strategies.

At the national level Aqua-Adapt should be one of the tools used to design and implement the NAP (see Table 4 in Chapter 1), ensuring that aquaculture has the necessary resources and access to adaptation options and implementation, and that actions in other sectors do not affect aquaculture's adaptive capacity.

Aqua-Adapt process includes six steps for the stablishment of an adaptation strategy (Figure 7):

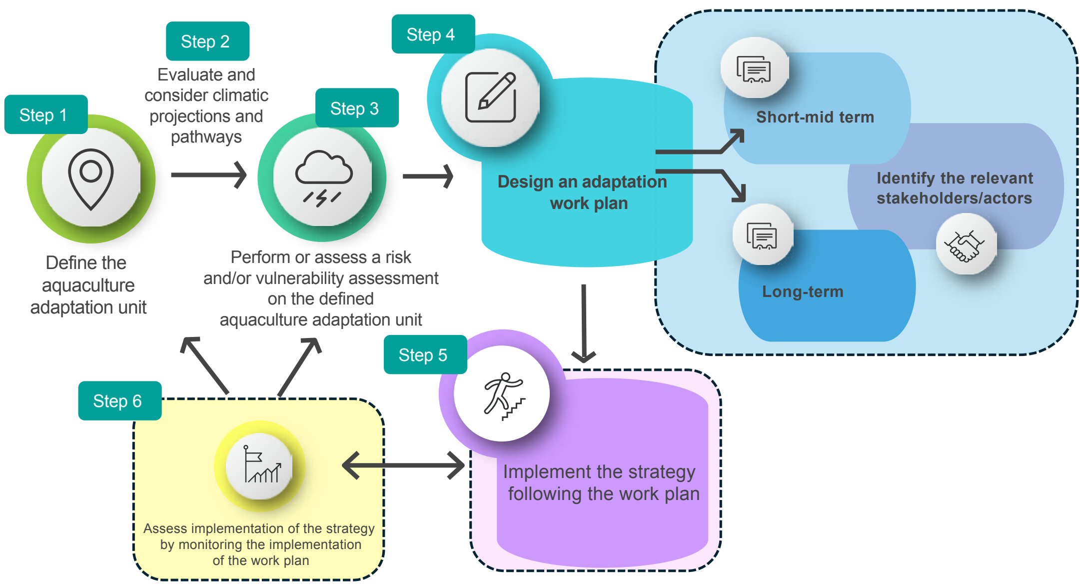
Step 1: Define the aquaculture adaptation unit, from individual farmers to the minimum geographical geopolitical area of adaptation, taking into account the farmed species/systems and associated socioecological systems at appropriate spatial scales.

Step 2: Evaluate and consider climatic projections and pathways including selecting appropriate regional climate model, selecting the temporal scale; few years, decades, etc. and climatic scenarios.

Step 3: Perform or assess a risk and/or vulnerability assessment on the defined aquaculture adaptation unit, fed with the best available information including climate projections for specific scenarios.

Step 4: Design an adaptation work plan to reduce risks, considering temporal scales for implementation; choose the best adaptation options taking into account the effectiveness of measures, costs, and technical difficulties. Co-benefits of adaptation

FIGURE 7
Aquaculture Adaptation Framework for Climate Change (Aqua-Adapt)



measures and the potential for maladaptation (as defined by IPCC, see definition in page 42) must also be considered. Develop a work plan setting clear and measurable goals, defining roles and responsibilities for all the for all involved.

Step 5: Implement the strategy following the work plan. All of these should be supported by appropriate governance for the defined adaptation units including investment, research and development (R&D), training, extension support, and incentives. It is also very relevant having aquaculture in the NAPs because often adaptation options involve other sectors. Such is the case, for example, when dealing with freshwater scarcity where there may be competition for water access with agriculture.

Step 6: Assess implementation of the strategy by monitoring the implementation of the work plan, including accessing the outcomes set on step 4 and achieved on step 5. It is also necessary to regularly monitor the work plan implementation following the indicator set and making necessary adjustments. And to engage with all the stakeholders promoting period reviews to ensure the strategy remains relevant towards the objectives.

Note: One of the most challenging aspects of adopting and implementing Aqua-Adapt or any other adaptation approach is to have the appropriate governance to do it. The necessary governance structure as defined by recently published FAO Guidelines for Sustainable Aquaculture (FAO, 2025) should include at least: i) a well-prepared leading institution and or team at the appropriate scale and considering nested decision making processes (national, provincial, district, commune, locality, etc.); ii) a mechanism to coordinate institutions and private sector, civil society, research and innovation institutions, etc.; iii) appropriate policies and norms to implement adaptation actions and measures; and iv) sufficient economic and human resources to implement Aqua-Adapt.

The whole process must be carried out using the best available scientific information and local knowledge as appropriate and must be fully inclusive and participatory (paying attention to gender inclusion as well as relevant minorities), especially while choosing the best options for adaptation.

The Aqua-Adapt proposed here is one possible model. While there are other approaches and pathways, the simple stepwise approach proposed here can be modified in complexity and scope if needed.

This chapter presents the theoretical base on which Aqua-Adapt has been developed, focussing on step 1 to step 4 (see above), while Annex 1 presents a summary version of Aqua-Adapt as a tool to help designing a strategy to adapt aquaculture to climate change.

II. STEPS FOR APPLYING AQUA-ADAPT

i. Step 1: Define the aquaculture adaptation unit

Developing and implementing an aquaculture adaptation strategy requires a definition of the aquaculture adaptation unit – in other words, the target of the adaptation.

Generally, this implies a production sector and/or geopolitical area in which stakeholders including government, farmers, processors, markets, R&D institutions, local communities, etc., will take adaptation actions. Defining its boundaries is necessary to assess climate risks and vulnerability and to implement Aqua-Adapt strategy effectively.

The aquaculture adaptation unit can be, for example:

- the national aquaculture sector
- the aquaculture sector at a subnational geopolitical scale, such as in a province, district, state, community, etc.
- a geographical area – national, community or aquaculture zone, aquaculture neighbourhood, etc.
- a specific cultivated species group, e.g. catfish, salmon, tilapia, shrimp, mussel, etc.
- a specific producer, farm owner or company
- a farming site or other spatial, productive, or geopolitical unit
- a production system, e.g. ponds, cages, tanks
- part(s) of the aquaculture value chain, such as seed production (whether it is hatchery-based or depending on seed collection from wild stocks)

It is important to consider that different components of the value chain may have different levels of risk. Also, depending on the spatial scale and scope, adaptation approaches at different scales can be embedded – for example, from the national to the provincial to the local. Nevertheless, it should also be noted that if the adaptation unit is a territorial unit, the aquaculture species and systems in this unit may be exposed to different hazards – and, therefore, may experience different risks. On the other hand, if the target unit identified is a national aquaculture sector – for example 'tilapia industry' – the same species could be subject to different risks when cultured in different territories, countries, etc. In these cases, it makes sense to work with smaller adaptation units – for example, corresponding to existing geopolitical districts or areas where the species is farmed.

It is more likely that national and local governments will favour territorial adaptation units because of the existing governance structure, regulations and policies in the territories. By contrast, it is more likely that the private sector will focus on specific species of interest and on the spatial distribution of their assets.

For example, as described in the case studies (Chapter 3), in Chile national authorities decided to prepare sectoral climate change risk maps across the country's territory. Chilean aquaculture is mainly composed by salmon farming and mussel farming, which make up more than 95 percent of annual production. Risk maps for salmon farming used the established salmon farming areas as adaptation units, while marine areas under each municipality were used as adaptation units for mussel farming (Soto *et al*., 2020). In each case, the decision was based on the distribution of farms and the availability of information.

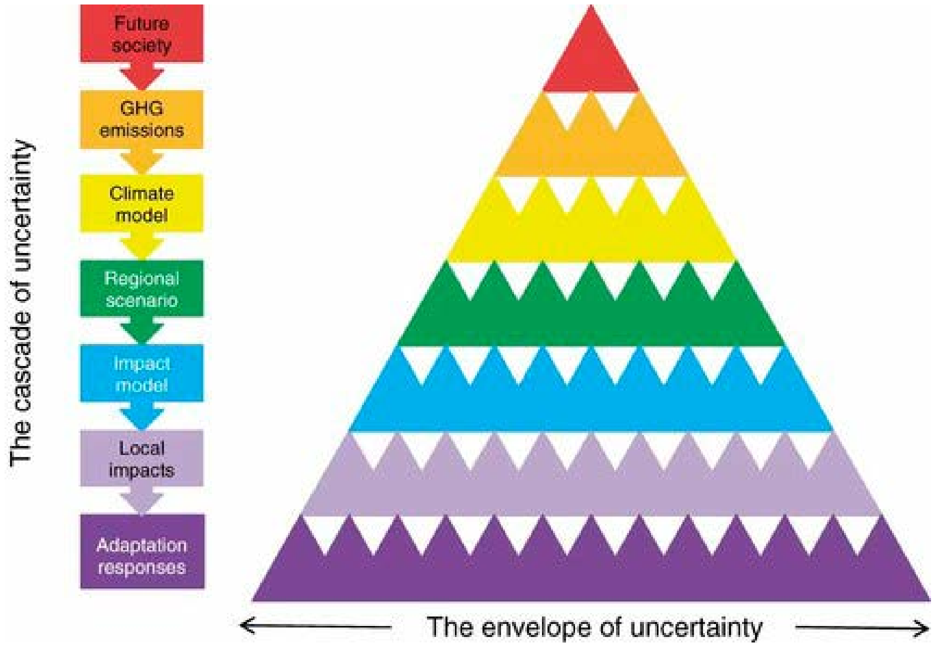
ii. Step 2: Evaluate and consider climate change projections and pathways

Explore and select climate change scenarios (IPCC, 2021, 2022a), these scenarios, known as Representative Concentration Pathways (RCPs) or Shared Socioeconomic Pathways (SSPs) in more recent models, consider various factors like economic growth, population changes, energy production, and land-use changes. They provide a framework for understanding how different policy and lifestyle choices can impact the climate. It is recommended to use the worst-case scenario model, RCP8.0, because it should generate the most resilient response. General scenarios, climate pathways and their impacts are available for large regions and ecosystems globally and it is possible to identify general hazards to fit into the risks assessments (next step).
It is necessary to evaluate the predictions and or projections by:

- selecting an appropriate regional climate model[3];
- defining a temporal scale – 10-year, 50-year, 100-year, etc., and

[3] IPCC provides regional climate models and projections updated with each scientific report. https://www.ipcc.ch/report/ar4/wg1/regional-climate-projections/

FIGURE 8
The cascade of uncertainty



Source: **Wilby, R.L. and Dessai, S.** 2010. Robust adaptation to climate change. *Weather* 65(7): pp. 180–185. https://doi.org/10.1002/wea.543

- selecting a scenario model to perform the assessment. These scenarios are known as RCPs or SSPs.

Being aware of the current trends and forecasts for the next few years, decades, and even the rest of the century is of paramount importance in formulating aquaculture's response to climate change.

This step is necessary to identify and predict the most important hazards, to guide adaptation actions and timetables.

Identifying trends and changes in the long-term is a very difficult step for farmers (especially small-scale), while governments should have a longer-term vision of the long-term risk and therefore they play a key role in providing information and guidance. This is a challenge for many countries, considering the cascade of uncertainty proceeding from GHG concentrations to global and regional climate model outputs and further to local impacts (Wilby and Dessai, 2010; also see Figure 8), especially so because most of the current climate models are geographically coarse and are not necessarily useful when the adaptation unit is very remote, small, or lacks objective information (supported by science or hard evidence of any kind).

iii. Step 3: Perform or assess a risk and/or vulnerability assessment on the defined aquaculture adaptation unit

Performing a risk assessment is essential to understand the magnitude and extent of potential losses due to climate change, in this case for the aquaculture sector.

Before understanding Aqua-Adapt's proposal to assess the risks and vulnerability of the adaptation unit, some concepts will be introduced. The following definitions are used in accordance with the fifth and sixth IPCC Assessment Reports (AR5 and AR6) (IPCC, 2022a):

Adaptation in human systems is defined as the process of adjustment to the actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities. In natural systems, adaptation is the process of adjustment to the actual climate and its effects; human intervention may facilitate this (IPCC, 2022a). Adaptation plays a key role in reducing exposure and vulnerability to climate change. In human systems, adaptation can be anticipatory or reactive, as well as incremental and/or transformational. According to this same report, an adaptation process is taking place in various ways across regions and sectors.

Maladaptation is understood as any action taken to address climate change that inadvertently increases vulnerability to its impacts, essentially making the situation worse by creating new risks or exacerbating existing ones, even if the initial intention was to adapt positively; it means a response to climate change that unintentionally leads to increased negative outcomes or reduced resilience (IPCC, 2022b).

Climate change risk (R) is the potential for consequences resulting from a particular hazard, considering the likelihood, magnitude, and timing of these consequences. Climate change risk encompasses the potential adverse effects of climate change, including the interaction of hazards, vulnerabilities, and exposures.

The components of risk are:

- **Hazard (H)** refers to the potential for a physical event or phenomenon to cause harm or damage to a system. This can encompass a wide range of natural and human-induced direct hazards, in the present case resulting from climate change (associated to the increase in greenhouse gas emissions (GHG)) such as temperature rise, temperature extremes, hot spells, precipitation changes (droughts), changes in season (early, late), sea level rise, extreme weather events, ocean acidification, salinization, hypoxia and oxygen dead zones. Indirect hazards include disease outbreaks, inability to spawn (e.g. too hot to spawn), toxic algal blooms, etc. (see Figure 3, in Chapter 1).
- **Exposure (E)** refers to the presence of people, infrastructure, production or natural systems in areas that are subject to the impacts of climate change hazards and that could be lost or damaged. This is essentially the measure of the extent to which a system is exposed to a particular hazard, considering factors such as geographical location and vulnerability of assets. As far as aquaculture is concerned, climate change exposure is the extent to which aquaculture systems and their dependent communities are subject to potential harm due to climate change. This includes exposure to direct and indirect climate-related hazards that can significantly impact the productivity, sustainability and socioeconomic viability of aquaculture operations.
- **Vulnerability (Va)** refers to the degree to which a system is susceptible to, and/or unable to cope with, the adverse effects of climate change, including the severity of the impact and the ability to recover. Thus, vulnerability has two components sensitivity and adaptive capacity.
  - **Sensitivity (S)** refers to the degree to which a system can be affected by climate variability due to the natural susceptibility of the ecosystem and of the features of aquaculture farming, species, habitats, livelihoods, aquaculture-dependent communities, etc. that make them more prone to be affected. For example, poorly managed fish, stressed fish, and weak or absent biosecurity are all conditions that make aquaculture more susceptible to climate change impacts.
  - **Adaptive capacity (AC)** is the ability of a system to adjust to climate change related hazards (including climate variability and extremes), to moderate potential damage, to take advantage of opportunities, or to cope with the consequences. This capacity may be influenced by the technological, financial, institutional, organizational and human resources available including the access

to species or varieties with wider tolerance to changing conditions (see Brugère and De Young, 2015).

Risk assessment can be carried out for aquaculture systems and for the production of aquaculture-related livelihoods, aquaculture species, and so on. It can also apply to a range of areas (Bondad-Reantaso, Arthur and Subasinghe, 2008). According to IPCC (2022a), the current definition of 'risk' related to climate change impacts has retained the notion of 'hazard' to describe the climatic driver of a risk. This is consistent with the definition of 'hazard,' which also focuses on the potential for negative consequences. Referring to a climatic event or trend as a 'hazard' thus relies on an assessment of its potential consequences, not only an assessment of the observed or projected change in a climate variable on its own.

The concept of risk is central to AR6 (IPCC, 2023). Risk framing and the concepts of adaptation, vulnerability, exposure, resilience, equity and justice, and transformation, provide alternative, overlapping, complementary and widely used entry points to the literature assessed by IPCC AR6's Working Group II (WGII).

The WGII report, which is the most relevant to aquaculture risk (Box 1) provides a framework for understanding: the increasingly severe, interconnected and often irreversible impacts of climate change on ecosystems, biodiversity, and human systems; differing impacts across regions, sectors and communities; and how to best reduce adverse consequences for current and future generations. In the context of climate change, risk can arise from the dynamic interactions between climate-related **hazards** and the **exposure** and **vulnerability** of affected human and ecological systems.

These considerations apply not just to risks related to climate change impacts but equally to risks related to responses to climate change, including adaptation and mitigation technologies, investments, practices and behaviours, and policies (Box 1). This is important because some risk reduction responses (adaptation, prevention, etc.) can inadvertently generate new threats (maladaptation).

BOX 1

Relevant questions aiming at characterizing risks related to climate impacts and to adaptation responses

According to AR6, informed decision-making requires a careful and transparent characterization of risk, considering both its *adverse consequences* and its *potential*:

- What are the magnitude, reversibility, distributional effects, etc. of the adverse consequences?
- How confident are *we* in our understanding of those aspects?
- How much do those consequences depend on socioeconomic trends or other assumptions?
- How well do we understand the *potential* for such events/outcomes to occur, and how much does this potential depend on climate change, policy design, or socioeconomic variables?
- Can we quantify the probability of occurrence? If not, can we characterize the *potential* in some other way that helps stakeholders decide whether to take this potential seriously, and how it compares with potential adverse consequences from alternative courses of action?

Source: modified from **IPCC (Intergovernmental Panel on Climate Change)**. 2022. *Climate Change 2022: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844.

a) Perform the risk and/or vulnerability assessment

As described above, **risk (R)** of climate change impacts is considered as a function of *hazard* (H), *exposure* (E), and *vulnerability* (Va). Risk in this context is understood as the potential for adverse outcomes when hazards interact with vulnerable and exposed systems.

Risk = f (E, H, Va)

where Va = f (+S, -AC)

IPCC (2014) formula R = f(+H), f(+E), f(+Va)

f(+H) indicates that risk is a function of **H**.

The (+) sign suggests that an increase in the hazard (e.g. more frequent or severe weather events) increases the risk. Hazards for aquaculture are extensively described in the literature (see Figure 3 in Chapter 1). The (-) indicates that Va decreases when AC increases.

b) Identifying the most important hazards to guide adaptation and timing of actions

Once there is some information on climatic projections for the adaptation unit (see step 2) it is necessary to identify the chain of events related to the main hazards; for example and increase in regional air temperature may drive oxygen declines and hypoxia events in freshwater ponds. This becomes the more immediate hazard to aquaculture production. In many cases there could be several hazards related to climatic projections and it may be necessary to prioritize those according to their relevance and time scale. In several cases, especially in Asia and Africa, efforts to identify more immediate hazards have involved consulting stakeholders about their perceptions (see Chapter 1, Literature Review), with the findings being used to develop risk and vulnerability indicators.

As shown above, risk is also a function of **exposure (E)**. The definition of what could be lost (aquaculture production, livelihoods, etc.) should be agreed through a participatory process.

In addition, risk is a function of **vulnerability (Va)**. The (+) sign suggests that greater vulnerability increases the risk.

Va = f(+S), f(-AC)

This part of the formula further elaborates on **vulnerability (Va)**, breaking it down into its components of sensitivity and adaptive capacity: **f(+S)** signifies that vulnerability is a function of **sensitivity (+S)**. Sensitivity is the degree to which a system or species is affected, either adversely or beneficially, by climate variability or climate change. The (+) sign means that higher sensitivity (e.g. a crop that is more prone to drought stress) increases vulnerability. As described above, several factors could make a system more susceptible to damage, for example a crowded and stressed fish farm is more likely to be affected by increased temperatures than a farm where fish are relaxed at lower densities. Other external factors could also be relevant, for example the extent to which water use by other sectors within the same watershed could render aquaculture more sensitive.

f(-AC) indicates that vulnerability is inversely related to **adaptive capacity (AC)**. Adaptive capacity is the ability of a system, community, or society to adjust to climate change (to moderate potential damages, to take advantage of opportunities, or to cope with the consequences). **The (-) sign suggests that higher adaptive capacity reduces vulnerability and could thereby reduce the overall risk.**

Resiliency in this simple model can be considered as opposed to vulnerability, but it is composed of those aspects of sensitivity and adaptive capacity that can be practically modified to make the system stronger to withstand the impacts and to mitigate the effects of climate change.

The main outcomes of a risk assessment are i) identification and estimation of the risk components; ii) risk values; and iii) the possibility to compare risk level for different areas or adaptation units and identify those with higher risk that require more urgent actions. When there are risk evaluations for a number of aquaculture areas it is the possible to create risk maps (see Chapter 3, case studies).

The estimation of the components of risk – namely hazard, exposure, sensitivity and adaptive capacity also brings an understanding of how risk could potentially be reduced by modifying (some of) these components. In the case studies we describe in Chapter 3 we use a simple semi-quantitative assessment of these components and estimated risk as R = H x E x Va.

Note of caution: The Aqua-Adapt proposed here is based on the most recent IPCC model.[4] While there are other approaches and pathways, we have chosen a simple stepwise approach that can be modified in complexity and scope if needed.

It is also important to stress that in the present context, a risk value resulting from an assessment mainly has a comparative value. It is useful for comparing risks among different systems or adaptation units to prioritize actions, and it is useful for evaluating risk reduction over time for the same unit after some adaptation measures have been put in place.

Annex 1 is a summarized stepwise model of Aqua-Adapt serving as a guidance for its implementation.

iv. Step 4: Design an adaptation work plan

The selection of adaptation actions should involve i) the reduction of risks and, if possible, ii) the use of new opportunities created by climate change. Indeed, adaptation could also involve taking advantage of new opportunities generated by climate change. For example, increased temperatures could enhance growth of some species such as tilapia, expand its farming range considering higher temperatures, etc. (Maulu *et al.*, 2021). However, considering available information, scientific evidence and pressing needs for increased resilience of aquaculture, Aqua-Adapt tool focuses more on the reduction of risks.

Reduction of risks must take into account the hazards (H) being confronted and must consider that <u>risks can be reduced</u> by: i) <u>reducing exposure</u> (E); and ii) reducing vulnerability (Va) which can be done by <u>reducing sensitivity</u> (S) and <u>increasing adaptive capacity</u> (AC) (IPCC, 2023).

a) Identifying and choosing the best available adaptation actions

As described in the literature analysis, several publications have explored potential adaptation "actions and measures"[5] (Chapter 1, Table 2 and Table 3). In most cases the exploration of actions must respond to the level of risk and the implementation timing of the strategy. Immediate – and probably more cost-effective – actions tend to be those that will provide benefits to the farm, aquaculture system, etc. even in the absence of climate change. This is the case with better management, which is also considered as a non-regret measure that improves the welfare of farmed fish, reduces stressful

[4] This model is an adaptation of IPCC AR5 and AR6. There are other alternative models such as that based on socioecological vulnerability (IPCC, 2021), e.g. Handisyde, Telfer and Ross (2017). They can also be useful.

[5] Through the text, the use of the term "actions" refers to the implementation of tools, instruments, innovations, etc., while "measures" is used to refer to a set of complementary actions. However, the use of both terms is often interchangeable as it is in the literature.

conditions, reduces densities, etc. Particularly important are biosecurity measures that reduce disease impacts, since these are often subject to climate change-related forcing factors such as increased temperature, reduced oxygen levels, and heightened susceptibility to diseases (Chapter 1, Table 2 and Table 3).

Ideally, actions and measures are more effective when they are tailored to reduce specific risk components, once hazards have been identified. However, non-regret or low-regret measures, such as improved biosecurity, can reduce risks in the face of many hazards and improve aquaculture resilience in general.

b) Considerations when examining options regarding adaptation actions

The actions described in Table 5A and Table 5B are intended to reduce identified exposure and sensitivity, and to increase adaptive capacity, in the short-, medium- and long-term respectively. It is important however to clarify that the proposed category of an action results from the participatory process pathway, and that actions and their impacts on risk reduction may not be independent from each other. For example, some actions to reduce exposure will also affect sensitivity; e.g. lowering farming biomass in a certain area will reduce the spread of diseases, therefore reducing sensitivity when diseases are not climate change-related. Also, some actions in certain contexts could either be classified as reducing sensitivity or as increasing adaptive capacity. Therefore, the process proposed to identify risk components and focused actions to reduce these risks is an operational process to facilitate discussions and participatory decision-making, and can be modified as appropriate.

Below we describe **some measures** that can be taken to reduce risks by modifying risk components. It should be noted that hazard is the one component which in general cannot be modified by the aquaculture sector alone especially given the minor contribution of aquaculture to global carbon footprint, unless there is firm global action to reduce GHG.

Adaptation measures that reduce exposure

The main measure identified to reduce **exposure** is the implementation of risk-based spatial planning. This implies the reduction of farming production in areas with higher risks when exposure is a relevant risk component, and the use of other lower-risk water bodies or watershed areas in the case of pond farming.

This will often involve high costs, including looking for alternative livelihoods if farmers and or investors are to remain in the high-risk areas. These measures can be implemented in the long-term and they can be very costly, especially for small farmers. Such is the case in many inland aquaculture areas in Asia (Islam *et al*., 2019).

In the case studies presented in Chapter 3, on marine salmon and mussel farming in southern Chile, one of the main risks associated with the 'reduction of precipitation' hazard is the increase of diseases and HABs driven by higher salinity and other drought-related changes in oceanographic conditions. The climate change risk maps elaborated for aquaculture (Soto *et al*., 2020, 2021) identified some areas that are more prone to such events, due both to a concentration of salmon production (high exposure, a component of risk which can be reduced), and also to high sensitivity, which in part is due to specific oceanographic factors that cannot be modified, such as low water turnover rate in some fjords, further reduced by a lower input of freshwater.

In this case exposure can be reduced by strategic spatial planning. Realistically, however, while this measure may be possible for floating fish cages located in a leased marine space (which is often the case for large-scale farming), it may be much more challenging or impossible for small-scale fishpond farming or for coastal shrimp farming because of the ownership of the land and access to water.

TABLE 5A
Some exemples of short- to mid-term (1 to 5 years) adaptation actions and measures to reduce risks (reduce exposure, reduce sensitivity, increase adaptive capacity) to face various hazards. Notice that the timing is relative since some short- term measures may continue and even be modified in the long-term

Adaptation options	Short- to mid-term actions					
	Actions/measures	**By government**	**By farmers**	**Public-private cooperation**	**Cost implications**	**Effectiveness of risk reduction**
Reduce exposure	Reduce farming production in higher-risk areas	Normative changes may be needed, also economic incentives and extension support	Implement changes to production in certain areas	Promote/implement incentives to move farming to other areas	Normally this has a relevant cost for the government and private sector	Mid to high
	Reduce aquaculture-dependent livelihoods in higher-risk areas	Support by aquaculture institutions and institutions outside the scope of aquaculture may be required	Learn new skills for alternative livelihoods	Promote/implement incentive systems for diversification of livelihoods		
Reduce sensitivity	Reduce farming densities that cause stress or health issues (disease, reduced animal welfare)	Research-based extension support	Implement changes to production densities	Promote/implement incentive systems such as certification of good practices	Considered 'low regret' actions (e.g. low cost and/or with additional positive effects)	Mid to high
	Improve biosecurity measures by adopting disease prevention measures such as vaccines, or using probiotics to enhance fish immune system, etc.	Normative changes may also be needed to promote research and extension support	Adopt biosecurity measures	Promote/implement incentive systems and cooperation mechanisms among farmers		
	Promote more efficient feeding processes and systems	Promote research and development, extension support	Adopt improved feeding systems	Promote/implement incentive systems and cooperation among farmers	It can be costly for low-income farmers	Medium
	Promote coordinated area management according to the carrying capacity of ecosystems	Research-based normative changes may be needed; often government-led	Adjust farming to comply with agreed management	Promote/implement incentive systems and cooperation among farmers		
	Promote IMTA and polyculture areas (area/ landscape scale)	Often government-led at regional and farming area scale	Learn new skills (farming other species), cooperate with other farmers			
	Protect, improve, regenerate forest cover and watershed management to ensure delivery of water quality and quantity	Government-led; scope often beyond aquaculture	Get involved, negotiate payment for forest ecosystem services	Promote immediate actions, mid- and long-term planning and cooperation between parties involved		
	Ensure aquaculture water (and space) use rights					

TABLE 5A (CONTINUED)

Adaptation options	**Short- to mid-term actions**					
	Actions/measures	**By government**	**By farmers**	**Public-private cooperation**	**Cost implications**	**Effectiveness of risk reduction**
Increase adaptive capacity	Implement climate forecast, environmental monitoring, and early warning systems	Government-led at regional and farming areas scale	On-farm monitoring can be useful	Public-private cooperation and coordination are needed to improve permanent on-site information and forecasting		
	Capacity to modify growing and harvesting timing (without affecting total production)	Extension support and promotion of some incentives (e.g. marketing)	Implement changes to harvesting with increasing flexibility	Promote/implement incentive systems		
	Implement advanced technology, AI, etc. to monitor farms and relevant ecosystems	Research and extension support	On-farm monitoring is often needed			
	Build stronger, more efficient farming holding systems, deeper ponds, etc.	Research and extension support, promote soft loans				
	Implement fencing and safety systems to protect from HABs, e.g. micro-bubbling curtains	As above	Farmers to adopt safety systems			
	Micro-bubbling and other oxygenation systems for floating cages and ponds	As above				
	Adopt IMTA systems at the farm scale and at the landscape scale (farming area)	Normative intervention needed considering strategic spatial planning; also normative changes may be needed to promote research and extension support	Farmers to adopt new farming activities, and/or willing to move farms			
	Ensure more resilient transport and access to farms, processing plants and markets	Government-led; scope often beyond aquaculture				
	Promote coordination mechanisms or public-private task forces to address impacts and build back better	Government-led	Coordinated farmers by farming areas	Public-private collaboration needed		
	Promote diversified livelihoods	Government-led, scope often beyond aquaculture; must consider avoiding similar exposure to common hazards				

Note: Many cells, particularly under 'cost implications' and 'effectiveness of risk reduction' are empty as they are highly context-specific and are meant to be filled through a participatory process.

HAB = harmful algal bloom; AI = artificial intelligence; IMTA = integrated multitrophic aquaculture.

TABLE 5B

Some examples of long-term (6–10 years or more) adaptation actions and measures to reduce risks (reduce exposure, reduce sensitivity, increase adaptive capacity) to face various hazards as described in the literature (Chapter 1) and in case studies (Chapter 3)

Adaptation options	Long-term actions					
	Actions	By government	By farmers	Public-private cooperation	Cost implications	Effectiveness of risk reduction
Reduce exposure	Implement risk-based spatial planning	Research-based decisions, normative changes may be needed; often government-led and supported with some incentives	Move farms, implement new farms in designated areas, etc.	Public-private cooperation needed to implement new/ improved siting	Costs are normally high for both government and for farmers and other stakeholders	In the long-term effectiveness should be high due to increased resiliency; however, risk-based spatial planning should be dynamic and must be monitored
Reduce sensitivity	Promote diversification of livelihoods	Research and extension supported, often beyond aquaculture scope	Adopt new livelihoods			
	Improve watershed management	Normative changes beyond aquaculture scope may be needed				
	Develop biotechnological tools and approaches to increase disease prevention and resistance (e.g. vaccines, immune stimulators, etc.)	Research and extension support, some normative changes may be needed				
Increase adaptive capacity	Adopt RAS systems	Research and extension support, promote soft loans	Adopt RAS systems			
	Use more resistant strains (e.g. to higher T°, lower O_2, higher salinity, etc.)	Promote research and innovation, technical support and extension; some normative changes may be needed	Adopt new strains	Public-private cooperation is often needed to implement the production of juveniles of adapted strains; cooperation and incentives needed to adopt new varieties	Costs of genetically selected strains can be high and normally require government funding related to research, innovation, production of selected seed, etc.	Effectiveness can be high when leading with one main hazard; e.g. when addressing increasing salinity in inland and coastal farming affected by sea-level rise
	Develop and promote farming of more resilient species	As above	Develop and adopt new species	Developing and adopting a new species is a long process that involves the whole value chain and where P-P and R&D is essential	Costs are usually high and often other reasons to diversify are needed	
	Use innovative technologies for water circulation and control in ponds	As above				
	Use submergible cages	As above				
	Use faster-growing species and strains	As above				
	Adopt more resilient feeds	As above				

Note: Many cells, particularly under 'cost implications' and 'effectiveness of risk reduction' are empty as they are highly context-specific and are meant to be filled through a participatory process.

P-P = Public-private cooperation; RAS = recirculating aquaculture systems; R&D = research and development.

Implement risk-based spatial planning

Spatial planning could be seen as part of a broader long-term strategic framework which governs the geographical location of farms, and it is normally led by government (Aguilar-Manjarrez, Soto and Brummet, 2017; FAO, 2017).

Moving the location of farms, and in some cases decisions on farming intensity per area or farming season, should be dealt with in aquaculture norms and regulations. However, in the case of climate change risk-based spatial planning, a more permanent, long-term relocation of production sites is often required, which necessitates robust knowledge of the areas that will be affected by the hazard.

Clearly there are costs for designing and then implementing this type of spatial planning. In addition, given that knowledge, including forecast is continuously increasing, a certain degree of flexibility may be advisable. This action could be developed at different spatial scales and it is likely to need the involvement of a regulatory authority; therefore, the cost of designing spatial planning will be public. However, implementation may involve costs for private farmers and/or farming companies. There are two types of costs involved. First, the cost of developing spatial planning (technical personnel, and acquisition of information relevant for decision making). Second, implementation costs and these are likely to depend on the restrictions over the use of space considered in the spatial planning, and the resulting reorganization of activities that derives from them. Costs could range from low to high, depending on how the ownership and the use of space and operational sites affects production. In some cases, farmers will opt for less costly technical innovations (in adaptive capacity) that will allow them to remain in high-risk areas (see case studies in Chapter 3). Additionally, they may use insurance to be prepared to mitigate impacts.

Adapting aquaculture to climate change – as in the case for most farming sectors – necessarily requires some flexibility in the way space and water bodies are used (e.g. through a leasing system). This is a major challenge for aquaculture regulation, and it requires urgent attention at a global level (Engler, 2024).

However, modifying the spatial distribution of aquaculture production – especially for freshwater and coastal systems – is often difficult, if not impossible. In many cases inland and coastal pond aquaculture is based on the formal and informal property or land-use rights of many small farmers living nearby, and it has been like this since ancient times. Furthermore, it can be impossible to find new locations to which aquaculture farmers can be moved, except in places where aquaculture is a new activity. For this reason, the spatial planning of aquaculture in part of Europe, Africa, North and Latin America and the Caribbean, where the sector is very new, could be considered as an opportunity under climate change. Conversely, spatial planning involving the movement of farms may not be an option in many countries in Asia.

Adaptation measures that reduce sensitivity

Among the measures that can reduce sensitivity, measures that will reduce the occurrence and extent of diseases due to climate change were specifically identified; they include the following:

- reducing farming densities;
- improving biosecurity through innovation and the use of biotechnologies such as vaccines to address likely disease increases; and
- promoting polyculture and integrated multitrophic aquaculture areas, thus avoiding monoculture (same species) in high-risk areas.

Other measures not directly involving aquaculture include:

- improving the conservation and better management of watersheds and landscapes, for example improving riparian vegetation, mangrove areas, etc., to diminish or mitigate flooding and to ensure water quality and quantity for aquaculture.

Reduce farming densities in higher-risk areas
This measure, consisting of reducing densities in individual farms, although classified under reducing sensitivity, is also related to the reduction of exposure.

The reduction of initial farming densities might reduce total biomass at harvest time, which could lead to an increase in total unit production costs. However, this is by no means inevitable: lower biomass during the growing cycle has advantages in terms of lower risk of fish diseases, less fish mortality, higher growth of individuals, and lower costs because of a reduced use of antimicrobial and other disease treatments. The net effect on total costs is uncertain, so a case-by-case analysis is required.

Reducing farming densities will decrease the number of individuals that can potentially be affected by a hazard, simply because there will be fewer individuals per farming site – but this does not *per se* affect the impact of the hazard on total biomass.

Moreover, there is ongoing discussion over the degree to which a high concentration of farmed individuals and the nutrients they release to the environment can act as a factor that facilitates the expansion, magnitude and persistency of hazards such as diseases, HABs and hypoxic events.

If this did turn out to be a factor, then reducing farming densities could have some impact on the propagation of the hazard, and hence reduce the sensitivity of the farming area. Such a measure could reduce risk in the mid to long-term, depending on the climatic context, farming scales, etc.

Improving biosecurity and farmed individuals' wellbeing will increase their resilience
Improving biosecurity and farmed individuals' wellbeing includes some specific measures such as enhancing fishes' immune systems, reducing stress factors (e.g. not enough oxygen, presence of predators) and preventing diseases (e.g. vaccines, probiotics), as well as increasing the distance between individual farms. These measures are non-regret actions that would improve farming sustainability and productivity even in the absence of climate change: disease is likely the single biggest hazard for aquaculture, especially in fish and shrimp farming.

Promote polyculture areas as opposed to monoculture
The idea behind developing a polyculture of different species in the same area is that these species will have different sensitivities to some types of **hazards**; this is especially relevant for minimizing risks of disease under climate change.

This concept also relates to integrated aquaculture (see below). The salmon farming case study (see Chapter 3) shows that Atlantic salmon is sensitive to sea lice, while 'Coho' Pacific salmon seems to be more resistant to this parasite – and even rainbow trout can withstand it more effectively (Gallardo-Escarate *et al*., 2019). Therefore, when water salinity increases due to drought, areas with mixed farming of two or three salmonid species could be less sensitive than areas with Atlantic salmon monoculture (Soto *et al*., 2020).

Polyculture at the scale of individual farms is on the other hand quite common in inland aquaculture in many places of Asia, for example the farming of various species of carps in the same pond in China, or the farming of shrimp, carp and prawns in some areas of Bangladesh (Islam *et al*., 2019) and is often described as mechanism to increase resiliency (Thomas *et al*., 2021). For example, different species in a pond could have different responses to increasing temperatures. However, despite the fact that several advantages of polyculture have been established, its financial return and economic performance remain poorly assessed with some few exceptions (Basu and Roy, 2021). Furthermore, there is not enough information regarding advantages for biosecurity and resiliency to diseases and not enough reported on their effect on areas beyond the farms.

Promote the implementation of integrated aquaculture

Integrated aquaculture (IA) (Soto, 2009; Ahmed, Thompson and Glaser, 2019), and IMTA (Chopin, 2013) are often described as options to increase adaptation to climate change. IA systems could reduce the sensitivity of farming under climate change, as farmers have a diversity of farmed species and products that will have different responses to a common hazard.

For example, farming aquatic species together with agricultural products that have different resistance to increased salinity or to drought periods reduces impacts on the farming areas. Such is the case of shrimp and rice farming in some countries in Asia where periods of increase drought and salinity are bad for rice but farmers compensate earnings through shrimp farming. Flooding on the other hand is often bad for shrimp farming but not for rice. According to Tran *et al.* (2020), farmers perceive that IA practices improve access to food and increase resilience and adaptive capacity to climatic risks. However, it is essential that the different farmed species have different responses to a common hazard, thereby increasing the resilience of the production system. For example, if an area is prone to extreme floods and/or major storms, hurricanes, etc., all farms and farmed species in that area will be at risk, no matter how integrated and diverse they are.

IMTA has also been suggested as an effective adaptation mechanism to protect molluscs from ocean acidification, because when farmed together with seaweed the latter can reduce CO_2 concentration and increase pH. However, seaweed farming requires a lot of space to increase pH in a significant way (Chopin, 2020), therefore in this instance IMTA needs to be strategically planned at the landscape scale – in which case government intervention is essential.

Protect and improve watershed management

In the case of freshwater aquaculture, the protection and regeneration of forest cover and improved watershed management can help ensure the delivery of the quality and quantity of water required for ponds and hatcheries. For example, Leon-Muñoz *et al.* (2023) illustrate the landscape dependency of salmon hatcheries and freshwater fish farms that produce juvenile salmonids. The publication also elaborates on climate change risk maps for salmon farming in the freshwater phase (Soto *et al.*, 2020), and shows how protecting watershed forests can reduce sensitivity – and therefore risks – for juvenile salmon production under the increasing droughts induced by climate change.

The protection of watersheds may be essential for freshwater fish farming at a global level, especially to reduce losses due to floods and droughts (Bueno and Soto, 2017). However, it is to be noted that the implementation of such measures is beyond the capacity of farmers, and aquaculture institutions often lack the necessary decision-making authority, therefore it is essential that aquaculture is considered in NAPs.

Measures that increase adaptive capacity

Implementing/improving strategic and integrated monitoring and early warning systems

Monitoring of the aquatic environment in aquaculture farming areas is key to detect changes that may negatively affect farmed individuals, infrastructure, value chain, etc. Integrated monitoring systems involve continuous measuring and reporting of some variables (which can range from very complex to very simple) in strategic locations within a connected ecosystem in such a way that the information can be integrated in a GIS or in a simple database, when information is collected by farmers themselves.

Ideally farmers should get involved in the monitoring of their farms and farming areas, however this often requires both training and coordination to manage the information, thus local institutions and government play a key role in providing such support (FAO, 2017; Bueno and Soto, 2017).

The information collected should be periodically assessed and evaluated by a technical team that can detect early warning signals and can provide feedback to users to consider when making management decisions. Local monitoring systems implemented by individual farmers can also be very useful in providing early warnings. Depending on the hazards identified, these systems can prompt farmers to harvest early, increase water oxygenation, strengthen farming structures, protect farms from HABs, etc. (FAO, 2017). Rapid and effective early warning measures can save production, or part of it – and can also sometimes reduce damage to infrastructure, or even save farmers' lives.

Modifying growing and harvesting times without reducing total harvest and production in the evaluated areas

This can be done to shorten or avoid exposure to more risky weather or adverse environmental conditions including diseases and pests. For example, to reduce risks during salmon fattening in marine cages, it is possible to increase the time that the fish spend in freshwater land-based farms beyond the smolting size[6] (see case study, Chapter 3).

This measure allows farmers to adjust the timing when fish go into the marine environment, avoiding summer or periods with higher risks due to parasites or HABs caused by climate change. The final production to harvest does not change (this is the indicator used as exposure in the case study), as a result of adapting to climatic variability and related trends.

For fish to spend more time in on-land enclosed systems, there is a need for various technological innovations and advances, including i) improved land-based facilities, and ii) genetic selection of faster-growing strains and/or strains that can spend more time in the freshwater cycle, so time spent in exposed areas can be reduced. Faster growth in inland facilities can also be assisted by improved fish feeds. Changing farmed species to other faster growing and more resilient species that need to spend shorter time in the more exposed situations is also a possibility. This seems to be the case in the Chilean salmon farming where Atlantic salmon (*Salmo salar*) was replaced by coho salmon (*Oncorhynchus kisutch*) in several areas, given the latter species higher resistance to sealice and diseases and considering its faster growth in the sea.

As reported by Lebel, Lebel and Lebel (2016) farmers producing freshwater fish in cages in reservoirs of Northern Thailand modify both the stocking time and harvesting time as short-term measures to reduce risks under certain hazardous conditions such temperature increases or cold spells.

Moving farmed fish to improved and more resilient farming facilities such as recirculated aquaculture systems

Moving farmed fish to a recirculated system (e.g. RAS) is another measure to consider under adaptive capacity, since this will reduce the risk of most hazards because farming conditions can be closely controlled (e.g. temperature, oxygen, diseases, etc.). However, it is very costly, and it may not be climate-smart due to the high energy inputs required. Nevertheless, this drawback could be overcome with rapid innovation in using solar or wind power, or other clean energy sources. Yet RAS systems currently, are probably too expensive for most small farmers both in freshwater and marine systems and there could be also space limitations and costs of available spaces on land for the RAS installation. However, other options such as partially controlled water circulation involving aeration in ponds can be a lower investment cost choice.

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[6] Size when the salmonids (anadromous fish) normally change their physiological system to move from freshwater to the marine environment.

Strengthening and deepening ponds

This is one of the most frequently cited measures to increase the adaptive capacity of freshwater and coastal pond aquaculture, since deeper ponds have more resilience to changing temperatures than shallower ponds and this can be a key triggering factor for other hazards, e.g. hypoxia, diseases. However, deeper ponds may require more effective water recycling systems. Therefore, it is always advisable to optimize pond design according to available water quantity and quality, and to general environmental conditions, to make the system more resilient to shocks.

Note of caution: The classification of the measures described above into the categories of reducing **exposure**, reducing **sensitivity**, and increasing **adaptive capacity** has been made for the purposes of the simple model used here. Thus, some measures which increase adaptive capacity– e.g. the use of RAS instead of floating cages – could also be considered as options to reduce exposure if the recirculating systems are in the same area. Since the components of **risk** that can be modified (E, S, AC) are given the same weight in this model, what is important is to understand and modify the components in a coherent way, such that risk reduction is promoted overall.

Cost-effectiveness of adaptation measures

Reducing farming production in higher-risk areas has various implications for the different actors involved, and may also have associated social costs. To implement this action, agents must have enough information about the **sites** with a higher probability of being affected by the hazard, and the government must have **instruments** or **incentives** to induce farmers to implement the proposed measure. The scale of production and the economic capacity of individual farmers as well as their social connection to the space being used will determine their response.

Large firms with several farms (most often aquaculture concessions or leases in lakes or marine areas) in different geographical areas can relocate their production from more exposed to less exposed areas, although this has relocation costs associated. The areas being used before a move are likely to be the most productive or profitable ones, so relocation is likely to lead to a permanent increase in total costs and a reduction in profits. Moreover, relocation to less exposed areas that are not being used brings start-up costs for farms which could include, for example, capital investment in infrastructure. It is also possible that relocation will increase operational costs, for example if new production sites are located in more remote areas.

Small farmers with only one or a few farms (aquaculture concessions) may face difficulties in relocating production. Private costs might be substantial, and it is necessary to add the potential costs of reduced income if the farmer is unable to sustain previous production levels to continue to supply contracts. In extreme cases, if the cost increase is very high the farmer might be forced to stop farming.

One mechanism that could lower adaption costs for both large and small farmers is the development of a secondary market for leasing aquaculture concessions. This could allow producers with concessions located in high-risk areas to rent concessions in less exposed areas, making it possible to maintain production and reduce total net costs. The development of such a market would probably require public involvement to create and to give legal status to the rules that would govern it.

Other potential social implications include the impact on workers who are unable to relocate or commute to a new area, or where the relocation costs are very high. If they are unable to get a new job that pays a similar salary to the old one, their household income will suffer.

Communities in isolated areas with a concentration of farms can experience reduced incomes when farm activities decrease, through a reduction in the provision of services that support production activities, and even a reduction in municipal revenues relating to the operation of aquaculture concessions. In the same way, when increased unemployment is concentrated in specific locations it can generate diverse social costs in a community. It is very important that no adaptation measures end up creating higher long-term social costs than the hazards which they are designed to address.

Cost-effectiveness considerations for choosing the best options over time

As described above, management measures can be more or less effective depending on the hazards involved, the context of all the risk components, and the timing of the response – moving towards a more adapted and resilient condition is a continuous ongoing process (Figure 7). It is also important to consider the costs (both private and public/government) of all measures involved.

Some measures could be appropriate for reducing the risks associated with various hazards, and their projected risk reduction can be considered an estimate of their effectiveness – this is well explained in the case studies (Chapter 3). We must also emphasize that the adaptation measures discussed here can also be implemented for reasons unrelated to climate change, which could be relevant from a cost's perspective – for example, RAS could be developed because marine space is scarce or unavailable.

Below we examine in more detail the potential cost implications of several measures.

– ***Modifying growing and harvesting times*** (time of stocking, growing period, harvest time) has private costs associated, which can be lower than reducing total production or moving the production to other areas. One important prerequisite for this action to be effective is to have reliable and timely information about the **moment** and **sites** that will be affected by the hazard. By choosing when to initiate or terminate the production cycle, farmers can partially or totally avoid the impact of the hazard – although this may mean that production takes place at a time that is less optimal than it would be in the absence of such considerations. This might result in some costs for the farmer in terms of smaller harvested fish and less total biomass, which might affect total profits. However, if profits are reduced in the most exposed areas, large farmers and companies can relocate production to less exposed areas, as analyzed in the salmon case study (Chapter 3).[7]

If costs for these two actions are compared – e.g. reducing total production vs reducing the farming time or shortening the farming cycle – the costs of reducing farming in the most exposed areas will probably be higher, both privately and socially, than of modifying growing and harvesting times. Nevertheless, this may not be the case for all stakeholders, which reflects the unequal distributive effects that such actions might have among different groups.

However, the effectiveness of the actions could also differ, making the reduction of farming in the most exposed areas a more effective risk-reduction measure than modify growing and harvesting times. Thus, it is not obvious which measure is the most cost-effective, therefore it is necessary to analyse carefully both; costs and effectiveness.

Finally, it is important to note the different assumptions underlying these two measures: that the location of the hazard is known in the first case, and that both the

[7] For example, in the case of Chilean salmon farming, this measure requires a review of the current regulation on following periods for salmon farming areas (SFA). In a sense, this regulation can be interpreted as a short-term (temporary) relocation measure. Productive operations are allowed in some locations, within a restricted time cycle. However, this measure does not consider the risk of a hazard such as a HAB when defining the production time window.

location and time of the hazard is known in the second case. The knowledge required to implement these measures is different in each case, which could also influence the choice between them. In other words, there are costs associated with the acquisition of information that differentiate the measures.

– ***Adoption of closed recirculating systems (RAS).*** The adoption of RAS is a long-term solution that isolates the activity from the impact of most hazards in natural oceanic conditions. It may or may not be a useful measure to implement as part of a risk-based spatial planning strategy. It is a long-term solution because it requires cost-feasible technology and an institutional framework for its development. It may be applied as a measure to deal with climate change hazards, but it can also be driven by other considerations. The cost of implementing RAS will be faced privately by individual firms; however, it may also involve public expense to the extent that an institutional framework needs to be developed. The cost of introducing RAS is expected to be high, and it is an unlikely option for individual small-scale farmers – it will probably be more expensive than **relocating production sites** through spatial planning. However, this strongly depends on the availability of spaces and how costly it will be for private firms to follow new rules on the use of space for production purposes.

– ***Effective monitoring and early warning systems.*** Monitoring and early warning systems can be implemented at different geographical scales and by different actors. For example, government agencies might provide information to the public in certain areas to make them aware of potential hazards like HABs, pests, etc. which could have effects beyond aquaculture production (health impacts, seafood safety, etc.) (see FAO, 2017 and Bueno and Soto, 2017). Also, individual farmers or farmers' associations could take part in efforts to install and run a monitoring and early warning system. Because of the nature of public information produced by these types of systems, it seems sensible to avoid individual systems and either to coordinate between public and private efforts, or to coordinate among producers. The cost includes capital investment in equipment, and operational expenses to run the system and make the information it generates, available to interested parties. Undoubtedly advances in technology are making it possible to access simple but very powerful monitoring tools, for example for temperature, oxygen, and water colour and turbidity (Bueno and Soto, 2017; FAO, 2017). These measures could work in a synergetic and complementary manner with measures devoted to reducing sensitivity and exposure. For example, helping to identify more risky areas, geographical or temporal patterns of hazards, etc., that should be supplemented with measures that reduce farming densities and biomass in exposed areas.

– ***Adopt submergible cages and offshore aquaculture.*** These are technology-based measures. Their capital expenses are related to the renovation of infrastructure, deployment and maintenance, which will affect investment needs and potentially affect operational costs. The cost of adoption will be borne by fish farmers, and could be significant in the short-term at least.

– ***Innovative technologies as quick fixes.*** Salmon farming is likely the most technologically innovative aquaculture sector globally (Iversen and Hydle, 2023), since juvenile stages require both freshwater ponds or containment systems and adults are fattened in cages in marine environments. Advanced water bubbling and fencing/safety systems (e.g. micro-bubbling and curtains to stop HABs and some parasites such as sea lice) to protect fish from HABs and other pests are rapidly being adopted as quick fixes for sudden extreme events of this kind (see Chapter 3, case studies).

– ***Advanced oxygenation systems.*** The use of nanobubbles to increase oxygenation is seen as a good solution to face hypoxic conditions, to improve the condition of fish in the presence of disease, and to increase the feed conversion ratio (FCR). Additionally, microbubble systems are being used to mobilize the water column from the bottom up, and also around farms in order to reduce microalgae density in cases of HABs, and hence lessen their impact on fish. These quick-fix technologies may be less costly for farmers than reducing their total production, and could eventually allow them to remain with projected farming biomass in areas of high risk – however, there has not yet been enough monitoring and analysis of the results of such innovations to assess their cost-effectivity. Nevertheless, all these technologies have the scope for expansion to other aquaculture systems; for example, the use of microbubbles is already a technique used in shrimp ponds to increase wellbeing and FCR (Shin Lim *et al.*, 2021).

Exploring cost-effectiveness through a semi-quantitative exercise

A simple exercise to illustrate how cost-effectiveness can be analysed is developed in this section. Table 6, Table 7 and Table 8 describe a number of climate change adaptation measures (columns) and the evaluator's expert-guess assessment of effectivity (in terms of capacity to reduce risk) against different hazards (lines) using a Likert score system where **1** is equivalent to ineffective and **5** describes a highly effective maximum reduction of risk. Using a similar approach, a 5-scale point score is used for estimated comparative costs where **1** essentially incurs no additional costs and **5** is extremely costly.

Table 6 describes estimates for farmed fish in cages and describes the cost and effectiveness of measures for 5 hazards. Colour scales are used to highlight the more effective and more costly measures in each case. Additionally, cost-effectiveness is estimated by dividing cost by effectiveness and then divided by 5 to normalize results. Thus, the lowest values (and darkest blue) on the inferior lines and rows are the best, in the sense of being the most cost-effective measures or the 'lowest cost with maximum effect on risk reduction', and the highest values (red) are the worst, or 'very costly with minimum or no effect on risk reduction'.

Similar analysis is shown for farmed molluscs on longlines (mussels, oysters, etc.) (Table 7) and for freshwater fishponds (Table 8). In all the Tables adaptation measures are organized from less expensive (left) to more expensive (right); with the latter measures also likely to take more time to implement.

The case studies used to describe the implementation of this framework (Chapter 3) include a basic conceptual model for the cost-effectiveness analysis, using information from salmon farming and mussel farming in Chile. This can also serve as a guide for an analysis in any aquaculture system.

Note: The case studies used to describe the implementation of this framework (Chapter 3) include a basic conceptual model for the cost-effectiveness analysis, using information from salmon farming and mussel farming in Chile. This can also serve as a guide for an analysis in any aquaculture system. Simple modelling of potential risk reduction due to implementation of some measures can guide selection of best actions and measures.

TABLE 6

Cost-effectiveness matrix for some adaptation measures in marine fish farming based on authors' expert guesses for a "made-up" example representing most common hazards and options described in the literature (see Chapter 1) and in the case studies (Chapter 3)

Hazards	Improved monitoring and early warning (AI, IOT etc.)		Reduced fish densities		Optimize biosecurity		adapted feeds (probiotics, prebiotics)		Improved oxygenation (e.g. nanobubbles)		Flexible barriers, microbubbles		More resistant structures		Reduce production in areas of greater risks		Movingto RAS		Use better adapted strains	
	Effec		Effec		Effec		Effec		Effec		Effec		Effec		Effec	Cost	Effec		Effec	
>T°C (hot spells)	3		4		3		3		3		3		1		3		5	5	4	
<O_2 (hypoxia)	3		4		3		1		4		3		1		4		5	5	4	
Extreme weather	3		2		2		1		2		2		5		4		3	5	1	
>HABs	3		3		2		1		3		4		1		4		5	5	4	
>Pests and diseases	3		5		5		4		3		3		1		3		4	5		
>Salinidad	3		2		3		2		2		2		1		4		5	5		
	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost
Effectiveness and cost for various hazards	3.0	2	3.3	3	3.0	2	2.0	3	2.8	2	2.8	3	1.7	4	3.7	4	4.5	5	3.3	5
Cost-effectiveness																				
>T°C (hot spells)	0.13		0.15		0.13		0.20		0.13		0.20				0.27		0.20		0.25	
<O_2 (hypoxia)	0.13		0.15		0.13				0.10		0.20				0.20		0.20		0.25	
Extreme weather	0.13		0.30		0.20				0.20		0.30		0.16		0.20		0.33		1.00	
>HABs	0.13		0.20		0.20				0.13		0.15				0.20		0.20		?	
>Pests and diseases	0.13		0.12		0.08		0.15		0.13		0.20				0.27		0.25		?	
>Salinity	0.13		0.30		0.13		0.30		0.20		0.30				0.20		0.20		?	

Note: Effectiveness (Effec) is estimated based on 5 score points, where 1 = non-effective (red color) and 5 = very effective (reducing risks to a minimal value, represented by the dark green). Costs (Cost) are also estimated based on 5 score points from 1 as minimal (green) or negligible to 5 as a very expensive measure (red). Notice that cost of a specific measure is the same for all hazards. The average effectiveness (Av Effec) of a measure against different hazards is also estimated, and cost-effectiveness is calculated as (cost/effectiveness)/5 to normalize the value between 0 and 1. Values near 0 are optimal (darker blue) and those near 1 are the worst (red). In all cases color scales correspond to the scores indicated in each cell. ? = represent cases where the adaptation measures could be relevant but there is not enough information on their effectiveness. AI = artificial intelligence, IOT = internet of things, ToC = temperature, RAS = recirculating aquaculture systems and HAB = harmful algal blooms.

TABLE 7

Cost-effectiveness matrix for mussel (or other bivalves) farming in long lines based on authors' expert guesses for a "made-up" example representing most common hazards and options described in the literature (see Chapter 1) and in the case studies (Chapter 3)

Hazards	Improved monitoring and early warning (AI, IOT etc.)		Reduced mussel densities		Optimize Biosecurity		Flexible barriers, microbubbles		More resistant structures		Reduce production in areas of greater risks		Use better adapted strains	
	Effec		Effec		Effec		Effec		Effec		Effec		Effec	
>T°C (hot spells)	3		2		3		2		2		3		4	
<O_2 (hypoxia)	3		2		3		3		2		4		4	
Extreme weather	3		2		2		1		5		3			
>HABs	3		1		2		4		3		4		4	
Pests and diseases	3		4		5		2		2		4		?	
>Salinity	3		2		3		1		1		4			
<pH	3		1		3		3		1		3		4	
	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost
Effectiveness and cost for various hazards	3	2	2.0	3	3.0	3	2.3	3	2.3	4	3.6	4	4.0	5
Cost-effectiveness														
>T°C (hot spells)	0.13		0.30		0.20		0.30		0.40		0,27		0.25	
<O_2 (hypoxia)	0.13		0.30		0.20		0.20		0.40		0,20		0.25	
Extreme weather	0.13		0.30		0.30		0.60		0.16		0.27			
>HABs	0.13		0.60		0.30		0.15		0.27		0.20		0.25	
Pests and diseases	0.13		0.15		0.12		0.30		0.40		0.20			
>Salinity	0.13		0.30		0.20		0.60		0.80		0.20			
<pH	0.13		0.60		0.20		0.20		0.80		0.27		0.25	

Note: Effectiveness (Effec) is estimated based on 5 score points, where 1 = non-effective (red color) and 5 = very effective (reducing risks to a minimal value, represented by the dark green). Costs (Cost) are also estimated based on 5 score points from 1 as minimal (green) or negligible to 5 as a very expensive measure (red). Notice that cost of a specific measure is the same for all hazards. The average effectiveness (Av Effec) of a measure against different hazards is also estimated, and cost-effectiveness is calculated as (cost/effectiveness)/5 to normalize the value between 0 and 1. Values near 0 are optimal (darker blue) and those near 1 are the worst (red). In all cases color scales correspond to the scores indicated in each cell. ? = represent cases where the adaptation measures could be relevant but there is not enough information on their effectiveness. AI = artificial intelligence, IOT = internet of things, ToC = temperature and HAB = harmful algal blooms.

TABLE 8

Cost-effectiveness matrix for freshwater fish farming in ponds based on authors' expert guesses for a "made-up" example representing most common hazards and options described in the literature (see Chapter 1) and in the case studies (Chapter 3)

Hazard	Improved monitoring and early warning (AI, IOT etc.)		Reduced fish densities		Optimize biosecurity		adapted feeds (probiotics, prebiotics)		Improved oxygenation (e.g. nanobubbles)		Deeper ponds		Implement IMTA		More resistant structures		Reduce productionin areasof greater risks		Movingto RAS/closed systems		Use better adapted strains	
	Effec		Effec		Effec		Effec		Effec		Effec		Effec		Effec		Effec		Effec		Effec	
>T°C (hot spells)	3		4		3		3		3		4		3		1		4		5		4	
<O_2 (hypoxia)	3		4		3		1		4		4		4		1		4		5		4	
Extreme weather	3		2		2		1		1		3		1		5		4		4		1	
>Pests and diseases	3		5		5		4		3		2		4		1		2		4			
>Salininity	3		1		3		1		1		2		3		1		4		5			
	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost	Av Effec	Cost
Effectiveness and cost for various hazards	3.0	2	3.2	3	3.2	2	2.0	3	2.4	3	3.0	3	3	3	1.8	4	3.6	4	4.6	5	3.0	5
Cost-effectiveness																						
>T°C (hot spells)	0.13		0.15		0.13		0.20		0.20		0.15		0.20				0.20		0.20		0.25	
<O_2 (hypoxia)	0.13		0.15		0.13				0.15		0.15		0.15				0.20		0.20		0.25	
Extreme weather	0.13		0.30		0.20				0.60		0.20		0.60		0.16		0.20		0.25		1.00	
>Pests and diseases	0.13		0.12		0.08		0.15		0.13		0.30		0.15				0.40		0.25		?	
>Salinity	0.13		0.60		0.13		0.60		0.40		0.30		0.20				0.20		0.20			

Note: Effectiveness (Effec) is estimated based on 5 score points, where 1 = non-effective (red color) and 5 = very effective (reducing risks to a minimal value, represented by the dark green). Costs (Cost) are also estimated based on 5 score points from 1 as minimal (green) or negligible to 5 as a very expensive measure (red). Notice that cost of a specific measure is the same for all hazards. The average effectiveness (Av Effec) of a measure against different hazards is also estimated, and cost-effectiveness is calculated as (cost/effectiveness)/5 to normalize the value between 0 and 1. Values near 0 are optimal (darker blue) and those near 1 are the worst (red). In all cases color scales correspond to the scores indicated in each cell. ? = represent cases where the adaptation measures could be relevant but there is not enough information on their effectiveness. AI = artificial intelligence, IOT = internet of things, ToC = temperature, RAS = recirculating aquaculture systems, IMTA = integrated multitrophic aquaculture and HAB = harmful algal blooms.

Some take-home messages from the cost-effectiveness analysis for the selection of the best adaptation options

The examples and table design shown here (Tables 6, Table 7 and Table 8) can be adapted to any situation, and the scoring system can be modified and optimized according to available information. Filling the tables through participatory processes can foster ownership as actors at all levels get involved in generating adaptation plans.

Some measures can be useful to address risk due to different hazards; for example, in the case of fish farming in cages or in ponds, moving to RAS can reduce risks due to most hazards (see average effectiveness in Table 6, Table 7 and Table 8). However, this is the most expensive solution, therefore it has a very low cost-effectiveness in the short-term. The option *'reducing production in areas of greater risks'* is similar, but it may not be able to reduce risks under certain hazards (e.g. due to extreme events *vs* diseases). Also the space and areas to do this may not be available, therefore strategic planning of aquaculture becomes essential (FAO, 2025). In the case of mollusc farming (Table 7), developing strains better adapted to lower pH is particularly important in the long-term since this is one of the main hazards for these farming systems.

It is important to underline that diversification of aquaculture production through the search for new strains or farmed types and or better adapted species is a very common recommendation for adapting aquaculture to climate change. However, it may be challenging to find species or develop strains that can be adapted to all hazards. Clearly this is a process better fitted to address specific hazards, such as the increased salinity due to sea-level rise that will increasingly affect aquaculture in lowland areas such as Bangladesh, some areas of India, the Mekong, and the Nile Basin. Here, the search for strains of better adapted catfish (Minh *et al.*, 2022) and tilapia (Mehrim and Refaey, 2023) is ongoing. Yet other hazards, from increasing diseases to extreme weather events, remain. The development and adoption of new strains and species is costly, take time, and it requires government intervention and public-private collaboration. In the short-term it may not be a cost-effective measure, but in the long-term it can be.

In the immediate term, the most cost-effective measures appear to be *'reducing fish farming densities'*, *'improving monitoring and early warning'*, *'optimizing biosecurity'*, and *'improved/optimized oxygenation'*. These measures are also less costly being the former best and therefore it is also comparatively more cost-effective, but this is in the short-term. Finally, making more resistant farming structures is a good measure mainly to face extreme events and it can be more cost-effective than moving farms to lower risk areas, if this is the main hazard (Table 6, Table 7 and Table 8). As mentioned earlier strategic planning of aquaculture must consider all of the above (FAO, 2025).

v. Step 5: Implement the adaptation strategy

The proposed actions and measures of the adaptation strategy are implemented. To do this it is necessary that different stakeholders involved, while understanding cost and benefits, take on corresponding roles and sufficient human and economic resources are allocated. Often it will not be possible to implement the full strategy, but the risk assessment should be a guide to understand the riskiest situations and their likely impacts so that efforts can be prioritized. The ecosystem approach to aquaculture guidelines (FAO, 2010) as a strategy provide some guidance on the implementation process that could apply as well to an adaptation strategy. Developing a work plan (step 4) for implementing the strategy is essential, and this should be a transparent and participatory process with clear and realistic timelines and estimates of human resources and budgets required for the different activities. Implementing the strategy may require technical support and training considering economic, technical, social and environmental aspects.

vi. Step 6: Monitoring and evaluation

The actions and measures within the strategy should be monitored and evaluated to improve implementation, using timelines and indicators agreed by stakeholders involved in the development of the strategy. A new assessment of risk is required once the actions and measures are in place and the strategy has been partly or completely implemented. The strategy's theoretical success can be assessed in terms of reduced risk. However, its true effectiveness can only be assessed by the extent to which it reduces losses when it is faced with a real hazard e.g. a sudden extreme event like a storm, an oxygen drop or a HAB.

Table 9 provides a description of the proposed steps of Aqua-Adapt, also suggesting how and who should take the lead or be involved. This table can also be used as a checklist to plan the process and to monitor results.

TABLE 9
General description of Aqua-Adapt proposed steps

	To do	How	By whom
Step 1 – Define the aquaculture adaptation unit	Establish the unit of adaptation – the subject of adaptation usually involves the farmed species and associated socioecological system at appropriate spatial scales: • aquaculture geographical area (national aquaculture, aquaculture community, aquaculture zone, neighbourhood, etc.); or • aquaculture sector (e.g. catfish farming, tilapia farming, mussel farming); or an aquaculture-specific species (e.g. *Oreochromis niloticus*) • other spatial, productive, or geopolitical units • production systems (ponds, cages, tanks)	Consider national efforts to address climate change, for example the national adaptation plan (NAP). These often identify relevant national areas, provinces, etc. and often identify sectoral needs	Stakeholders could vary from national authorities to provincial and communal authorities, and also local ones. They could also include private-sector organizations

TABLE 9 (CONTINUED)

	To do	How	By whom
Step 2 – Evaluate and consider climatic projections and pathways	Select appropriate regional climate model Select the temporal scale – 10-year, 50-year, 100-year, etc. Select scenario. These scenarios, known as Representative Concentration Pathways (RCPs) or Shared Socioeconomic Pathways (SSPs) in more recent models, consider various factors like economic growth, population changes, energy production, and land-use changes. They provide a framework for understanding how different policy and lifestyle choices can impact the climate. It is recommended to use the worst-case scenario model, RCP8.0, because it should generate the most resilient response.	Use best scientific sources and expertise at the global, national and local level as appropriate	Stakeholders should include national experts and scientists as well as international support when needed
Step 3 – Perform or assess a risk and/or vulnerability assessment on the defined aquaculture adaptation unit	Perform a risk assessment considering hazard (H),hxposure (E), vulnerability (Va) and adaptive capacity (AC) following:		
Hazards	Establish climate change-associated projections for a certain period (e.g. the next 30 years, end of the century, etc.) and identify the main hazards. These may include **increasing (or changing) air and water temperature (as main drivers), oxygen reduction, salinity increase, sea-level rise, increase of pests and diseases, increase of extreme events, droughts and flooding, ocean acidification**	Use the best available information on past, current and projected events, including models, scientific knowledge, local knowledge, etc. Time scales should align with actions and measures Identify information gaps. This can be done with expert groups and local stakeholders using semi-quantitative approaches, e.g. with Likert-type scoring, or other more quantitative approaches and models as available	Research and monitoring institutions and other stakeholders. Local participation is always encouraged (there are plenty of examples where local perception has been used)
	Establish a chain of events/impacts associated with hazards; consider that there could be several hazards generating joint and often synergistic impacts		
	Prioritize main hazards		
Exposure	Establish/assess the production, assets and livelihoods that could be lost	Use the best available data on harvest/ production by location, species, livelihoods, etc.	Government, in collaboration with farmers and private sector
Sensitivity	Establish and assess factors that make the system more susceptible to be affected by climate change impacts (factors could be internal or external to the aquaculture system)	Use the best available information, often requiring ecosystem-level information, land-water interactions, aquaculture management aspects, biosecurity, etc. Identify information gaps	Government, in collaboration with farmers and the private sector, local knowledge etc.
Adaptive capacity	Establish and assess factors and conditions that can make the system more resilient and better prepared to face climate change impacts; for example the innovation capacity, the access to new technologies, extension and economic support, etc. It is also relevant to consider factors that will contribute to building back better and conditions that allow the identification of key gaps.	Use the best available information, from legal aspects, governance, financing, technologies, etc.; identify gaps	Government, in collaboration with farmers and stakeholders. If the adaptation unit is a farming company, it will use its own resources
Consider certainty	In any risk assessment, it is necessary to consider some indicators of certainty, especially when using hazard projection models. Also, the estimation of exposure and sensitivity involves using information that is often incomplete or lacking. Adaptive capacity options on the other hand can be identified and agreed among stakeholders	Establish some indicators of certainty. The quality and extent of available information is key	Government, in collaboration with farmers and private sector, local knowledge, etc.

TABLE 9 (CONTINUED)

	To do	How	By whom
Step 4 – Desing an adaptation work plan	Elaborate a work plan: • Establish the strategy governance, e.g. who will lead, how institutions and private sector will be coordinated, etc.; Identify adaptation options: • Identify strategies and options to reduce identified exposure and sensitivity, and to increase adaptive capacity; • Elaborate a timescale for implementation (short- to mid-term being 1 to 3 years; long-term being 4 to 6 years or more); • Select the most appropriate adaptation options/actions and mode of implementation; • Identify human and monetary resources for the implementation of the strategy; • Identify adaptation measures that the government can execute, e.g. sea defences, flood defences, mangrove planting; • Identify adaptation measures that science can manage, e.g. genetic selection for tolerance to new conditions; • Identify adaptation actions that farmers can implement, e.g. deeper ponds, higher dykes, nets on top of dykes, changing species.	Use the best available information and strategic approach, with adequate human capacity and resources Use cost-effectiveness indicators and the target level of risk and/or vulnerability to choose the best option. Low-regret actions[1] could be adequate as initial and short-term measures. Trade-off assessments could be useful. Costs could include research and development, accessibility, extension, actual onsite implementation, etc. The potential for maladaptation should be considered[3] Analysis of trade-offs could also include additional opportunities[4] Simple modelling of potential risk reduction resulting of some measures can be performed to guide selection of measures Timing for implementation should also consider the timing of projected hazards	Stakeholders involving government and the private sector, local communities, etc. at the appropriate geographical scale
Step 5 – Implement the strategy following the work plan	Proposed actions are implemented following work plan considering clear and realistic timelines and estimates of human resources and budgets required for the different activities	Use training and coaching to elaborate and implement the plan. Consider timing, resources, leadership etc. Cost-benefit analysis are often necessary	Government, private sector, communities
Step 6 – Assess implementation of the strategy by monitoring the implementation of the working plan	Implementation is monitored, and to evaluate its success it is possible to estimate risks again after actions are in place. This will be risk Rx, where x is the time when the strategy has been partly or completely implemented. The strategy's theoretical success can be assessed in terms of reduced risk. However, its true effectiveness can only be assessed by reduced losses in response to a real increasing hazard or sudden event	Design monitoring indicators, e.g. loss reduction. Perform new risk assessments after measures are implemented	Government, private sector, communities

[1] **IPCC (Intergovernmental Panel on Climate Change)**. 2022b: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. [2] **Galappaththi, E.K., Ichien, S.T., Hyman, A.A., Aubrac, C.J. and Ford, J.D.** 2020. Climate change adaptation in aquaculture. *Reviews in Aquaculture*, 12 (4): 2160–2176. https://doi.org/10.1111/raq.12427; [3]Climate change maladaptation includes adaptation measures that could indirectly increase the negative impacts of climate change and/or increase the vulnerability of the sector itself or across sectors (**Schipper, E.L.F.** 2020, Maladaptation: When Adaptation to Climate Change Goes Very Wrong. One Earth, 3: 409-414) and [4] **Pham, T.T.T., Friðriksdóttir, R., Weber, C.T., Viðarsson, J.R., Papandroulakis, N., Baudron, A.R., Olsen, P., Hansen, J.A., Laksá, U., Fernandes, P.G., Bahri, T., Ragnarsson, S.Ö. and Aschan, M.** 2021. Guidelines for co-creating climate adaptation plans for fisheries and aquaculture. *Climatic Change*, 164, 62. https://doi.org/10.1007/s10584-021-03041-z

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CHAPTER 3
Adaptation options and cost-effectiveness analysis for reducing the risks associated with climate change: two case studies from Chilean aquaculture

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I. INTRODUCTION

This chapter presents and discusses two examples of the process used to evaluate and choose adaptation options considering their effectiveness, their costs, and cost-effectiveness of risk reduction (and increased resiliency) in response to various hazards associated with climate change. The adaptation options were selected after the application of Aqua-Adapt developed and presented in Chapter 2. The exercise serves as an Aqua-Adapt field test although the effective process has not been completed in either case, therefore part of the process has been modelled.

The first case study involves the Chilean salmon farming sector. The adaptation units defined were the 20 salmon farming concession areas (SFAs) in the Los Lagos Region, one of Chile's 13 geopolitical districts. This case study represents a medium- to large- scale aquaculture activity. The study focused on the grow-out phase (fattening stage). This specific production phase will experience higher risks of parasitism due to increased salinity resulting from reduced precipitations as the main hazard.

A second case study describes the Chilean mussel farming system considering the risk of losing the harvest of wild mussel seed due to reduced precipitations that generate increased salinity in the fjords. The collection and farming of mussel larvae is essentially a case of small-scale aquaculture.

The two case studies used information from Chile's recent climate risk mapping project. The Chilean Ministry of Environment (MMA), in collaboration with national research institutions, organized the creation of climate change risk maps for various productive sectors (MMA, 2020), including aquaculture. Risk maps were created for Chile's two main aquaculture production systems: salmon and mussel farming. Using information from the Climate Risk Atlas for Chile, (ARClim) (Soto *et al*., 2020), our case studies scrutinize risk assessment, risk mapping, and risk reduction measures in each instance.

The purpose of presenting these case studies is to show how, with limited information, it is possible to follow the proposed Aqua-Adapt to support the decision-making process when choosing adaptation options to address climate change risks. The case studies have also provided an opportunity to modify Aqua-Adapt, and test its effectiveness as a tool for different aquaculture sectors.

The salmon farming case study is described here in much more detail than the mussel farming one, mainly due to the relative availability and quality of the information relating to it.

Note: The examples we consider explore the risk of losing the production biomass of farmed salmon and of losing mussel seed. The loss of aquaculture production can have serious social and economic consequences, affecting livelihoods locally and further afield (e.g. León-Muñoz *et al*., 2018; Soto *et al*., 2019); however, we do not explore these aspects in detail here. Nevertheless, the model and related analysis can easily be expanded to address such losses.

Brief overview of the Chilean aquaculture sector

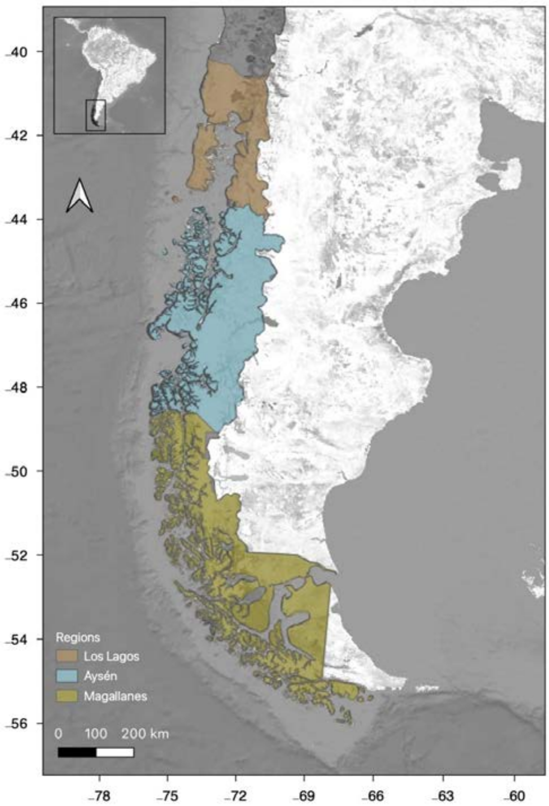
Chile is among the world's 10 largest aquaculture producers (FAO, 2024). It is the second largest producer and exporter of farmed salmon, with a production of nearly 1 million tonnes in 2023 worth about USD 6 000 million; and the largest mussel exporter, producing nearly 426 000 tonnes in 2021 with an estimated value of USD 225 million.

Salmonids are exotic species to Chile, and farmed species include Atlantic salmon (*Salmo salar*) with about 70 percent of production, Coho salmon (*Oncorhynchus kisutch*) with 18 percent, and rainbow trout (*Oncorhynchus mykiss*) with 12 percent. The freshwater phase of the salmon farming (eggs to smolt and juvenile individuals) takes place in land-based farms, while the grow-out or fattening phase takes place in floating marine cages. The farming is intensive: individual farms may harvest between 2 000 and 6 000 tonnes per cycle (16 to 18 months).

There are more than 400 farming sites distributed along the coastal fjords, channels and inlets of Patagonia between 42ºS and 54ºS. Farming sites are organized in some 68 salmon farming areas or neighbourhoods (SFAs) distributed among the three salmon farming regions, namely the national districts of Los Lagos, Aysén and Magallanes (Soto *et al*., 2019; Figure 9).

Chilean farmed mussel production, by contrast, is based on a native species (*Mytilus chilensis*). It is located in the Los Lagos district in Northern Patagonia, and unlike salmon, the industry is composed mostly of medium scale farmers for the fattening, processing and exporting stages. However, farmed mussel production relies on captured wild seed (or spat), which is essentially small-scale, capture-based aquaculture: this provides an opportunity for many local artisanal fishers using longlines in fjords and coastal waters. The mussel case study we discuss here focuses on the collection of its wild seed.

FIGURE 9
Main aquaculture districts/regions in Southern Chile: Los Lagos, Aysén and Magallanes



Note: Refer to the disclaimer on page [ii] for the names and boundaries used in this map.

Source: Adapted from **Soto, D., León-Muñoz, J., Molinet, C., Soria-Galvarro, Y., Videla, J., Opazo, D., Díaz, P., Tapia, F. and Segura, C.** 2020. *Informe Proyecto ARClim: Acuicultura*. https://arclim.mma.gob.cl/media/informes_consolidados/01_ACUICULTURA.pdf

II. USING AQUA-ADAPT TO DESIGN AN ADAPTATION STRATEGY FOR CHILEAN SALMON FARMING

i. Step 1 – Define the adaptation unit for salmon farming

The study area for the application of the case study is the Los Lagos district in Northern Patagonia, Chile (Figure 9); and the defined unit of adaptation is each of its 20 SFAs. Each SFA is a management area defined by the government to address a salmon disease outbreak in 2010 and they were chosen as adaptation units because current regulations allow specific management measures for each (Soto *et al.*, 2020). SFAs in the Northern part of this region are those likely experiencing the largest hazard in terms of most marked drought, and because of the largest exposure, these are the ones experiencing the highest risks.

ii. Step 2 – Evaluation of the climate projection pathways

As described above, the cases studies described here are based on an initiative leaded by the Chilean Ministry of Environment to develop climate change risk maps for various national sectors. The evaluation followed the guidance of the Fifth Report (AR5) and Sixth Report (AR6) (IPCC 2014, 2022) of the Intergovernmental Panel on Climate Change, in both cases following the analysis of IPCC AR6´s Working Group (IPCC, 2023). Climatic projections and threats considered the change in climate between the recent past (1980–2010) and the medium future (2035–2065) under a pessimistic scenario of GHG (RCP8.5). Historical and future climate conditions were obtained by considering the average of 20 to 30 simulations based on numerical models of the atmosphere (see details in the Climate Threat Explorer: https://arclim.mma.gob.cl/amenazas/). The model results were also downscaled and corrected so that they are currently unbiased with respect to the observed climate referenced in the CR2Met database (http://www.cr2.cl/datos-productos-grillados/).

Climate projections evaluations underscored the impacts of expected temperature increases and reduction in precipitation specially affecting central zone and Northern Patagonia. Both patterns already being experienced (see more at https://arclim.mma.gob.cl/atlas/view/acuicultura_f_salmon_fan/).

iii. Step 3 – Perform a risk and/or vulnerability assessment on the defined aquaculture adaptation unit

a) Risk assessment

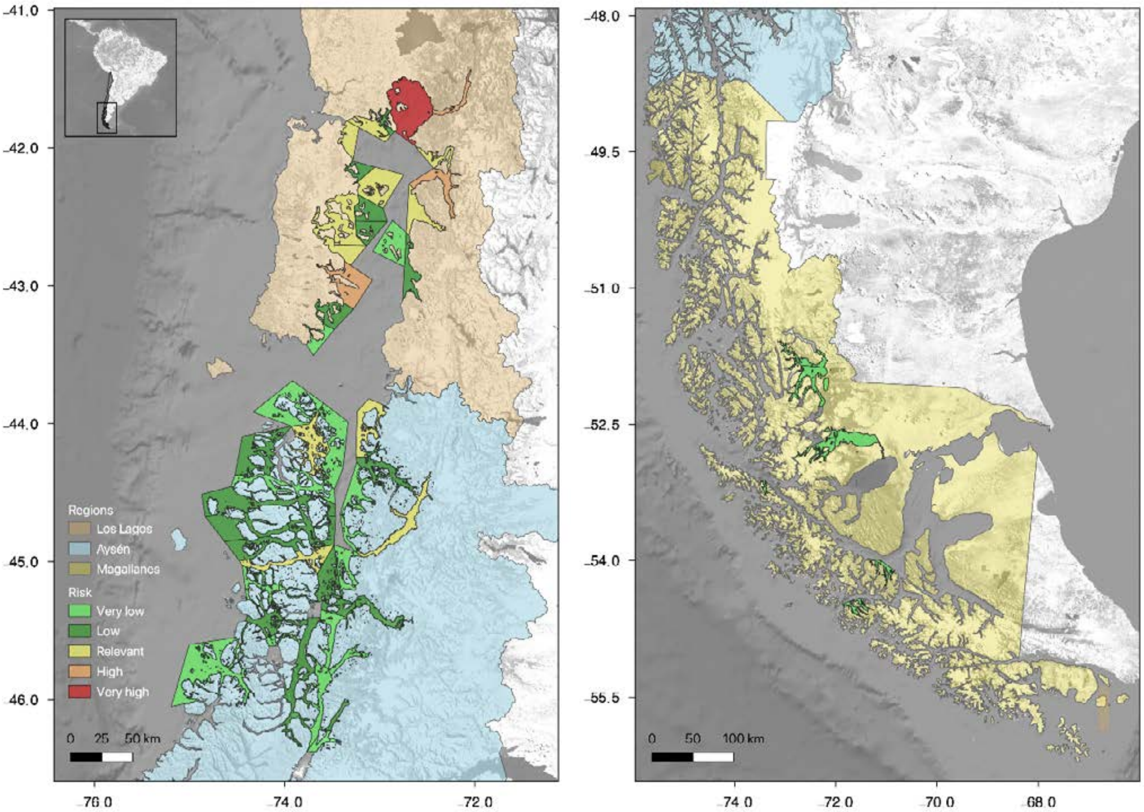
A climate change risk assessment was done for salmon farming covering the whole coastal marine area of Southern Chile, with increased HABs and parasitism as the main hazards, resulting in risk maps for the 69 SFAs (from 41ºS to 54ºS) (ARClim maps (see more at https://arclim.mma.gob.cl/atlas/view/acuicultura_f_salmon_fan/ and https://arclim.mma.gob.cl/atlas/view/acuicultura_f_salmon_para/)). Only the risk of increased parasitism is addressed in this example.

The risk maps represent the risk for the near future (2035–2060), compared to the historical period (1981–2010). The index varies between 0 and 1, where 1 is the maximum value (adapted from the Draft Chile National Adaptation Plan for Fisheries and Aquaculture). The highest risks of increasing parasitism were in the Los Lagos region of Northern Patagonia, mainly because higher hazard levels combined in some cases with high exposure and/or sensitivity (Figure 10, Table 10). For this reason, only the 20 Los Lagos SFAs were used to illustrate Aqua-Adapt process.

The assessment of the estimated risk components and final risk levels of each unit of adaptation was based on the existing monitoring systems for salmon production, biosecurity parameters (reports and information collected by National Fisheries and Aquaculture Service of Chile; Sernapesca) and available oceanographic information (Soto *et al.*, 2019, 2020, 2021).

FIGURE 10

Risk index of biomass loss (harvest) due to increased parasitism at each SFA (coloured polygons) because of increased salinity which is, in turn, a consequence of reduced rainfall. Colours of polygons represent comparative risks in a five levels scale from very low (light green) to very high (red). The three coloured section on land represent Los Lagos, Aysen and Magallanes Regions, from north to south



Note: Refer to the disclaimer on page [ii] for the names and boundaries used in this map.

Source: Adapted from **Soto, D., León-Muñoz, J., Molinet, C., Soria-Galvarro, Y., Videla, J., Opazo, D., Díaz, P., Tapia, F. and Segura, C.** 2020. *Informe Proyecto ARClim: Acuicultura*. https://arclim.mma.gob.cl/media/informes_consolidados/01_ACUICULTURA.pdf

TABLE 10

Climate change risk components – hazard (H), exposure (E) and sensitivity (S) – for the 20 SFAs, and the indicators used to build each identified risk

	Description	Indicators	Comments/ assumptions
Hazard (H)	**Reduction of precipitation resulting in a chain of events and effects**	**H value is a composite of several indicators (simple average) described below**	
Climate change driven chain of events impacting salmon farming	Less freshwater entering fjords and inner seas results in increased salinity, reduced ventilation and renewal time. Increased salinity can generate increased incidence of some parasites and diseases	Projected number of dry days on the expected drought frequency index were scored between 1 to 5, representing lowest to highest values (Soto *et al*., 2020[1], 2021[2])	There are no straightforward models directly connecting precipitation with parasitism in salmon, but there is plenty of information showing a correlation between increased salinity and higher sea lice survival and infestation rates (Soto *et al*., 2019[3]; Zalcman *et al*., 2021[4])
Exposure (E)	Salmon biomass that could be lost within each SFA	We used the average for total salmon harvested for the period 2017–2018* for each SFA, scored between 1 to 5, representing lowest to highest values (Soto *et al*., 2021[1])	Since the estimated risk values are comparative, total harvested biomass is used as a proxy. Losses due to sea lice could vary between 10 to 30% of expected harvest (Gallardo-Escárate *et al*., 2019[5])

TABLE 10 (CONTINUED)

	Description	Indicators	Comments/ assumptions
Hazard (H)	**Reduction of precipitation resulting in a chain of events and effects**	**H value is a composite of several indicators (simple average) described below**	
Sensitivity (S)	All (non-climate-change-associated) factors that could make the salmon loss greater	Final S value is a composite of several indicators (simple average) described below (S1 to S4)	
S1 – Freshwater dependency	Current freshwater influence affecting salinity and pycnocline in fjords and inlets. Areas with lower salinity have lower incidence of sea lice and gill amoeba	Current water density was scored between 1 to 5, representing lowest to highest values	Farmed salmon tends to have less parasites in areas with lower salinity (Soto *et al*., 2019; Lepe-López *et al*., 2021[6])
S2 – Accumulated harvested biomass	Areas which have a longer history of salmon farming and where more salmon has been produced are likely to have higher levels of parasites and pests	Accumulated harvested biomass (2010–2018) per SFA were scored between 1 to 5, representing lowest to highest values (MMA, 2020[7]; Soto *et al*., 2020, 2021)	
S3 – Previous salmon health condition	High densities and poor management exacerbate diseases (Figueroa *et al*., 2019[8])	Previous use of antimicrobials was used as a proxy. Total use per SFA during 2017–2018 was scored between 1 to 5, representing lowest to highest values	We did not use direct indicators of sea lice presence because they are correlated with current freshwater influence. We did not have information on the average farming density per farm
S4 – Atlantic salmon dominance	Higher dominance of one species (tendency to monoculture) will promote more diseases than mixed farming (e.g. the three salmon species). Additionally, Atlantic salmon is more prone to experience sea lice (Gallardo-Escarate *et al*., 2019[5])	We scored the dominance of Atlantic salmon from 1 to 5, with 5 representing 100%, meaning that all the farms in the SFA are farming this species	
Adaptive capacity (AC)	The adaptive capacity for the risk maps was considered as 0 (Soto *et al*., 2020[1]), since there was not enough information on specific measures to assess and compare the different SFAs. However, for the current exercise we have proposed some measures and technical innovations that allow risks to be reduced while not modifying exposure or sensitivity	For both salmon farming and mussel farming we have used a simple increase in AC consisting of the implementation of environmental monitoring systems. However, other examples of AC are also offered to complement the case studies	

Note: SFA = Salmon farming concession areas.

* Best available information for all the SFAs, provided by the National Fisheries and Aquaculture Service of Chile (Sernapesca; Soto *et al*., 2020, 2021[1,2]).

[1] **Soto, D., León-Muñoz, J., Molinet, C., Soria-Galvarro, Y., Videla, J., Opazo, D., Díaz, P., Tapia, F. and Segura, C.** 2020. Informe Proyecto ARClim: Acuicultura. https://arclim.mma.gob.cl/media/informes_consolidados/01_ACUICULTURA.pdf; [2] **Soto, D., León-Muñoz, J.,** [2]**Garreaud, R., Quiñones, R.A. and Morey, F.** 2021. Scientific warnings could help to reduce farmed salmon mortality due to harmful algal blooms. *Marine Policy*, 132: 104705. https://doi.org/10.1016/j.marpol.2021.104705; [3] **Soto, D., León-Muñoz, J., Dresdner, J., Luengo, C., Tapia,** [3] **F.J. and Garreaud, R.** 2019. Salmon farming vulnerability to climate change in southern Chile: understanding the biophysical, socioeconomic and governance links. *Reviews in Aquaculture*, 11, 354–374. https://doi.org/10.1111/raq.12336; [4] **Zalcman, E., Burroughs, A., Meyer, A., Hillman, A., Sadler,R., Madin,B., Mackenzie, C., Ward, MP., Stevenson, M., Happold, J., Hutchison, J., Gallardo AL, Cameron, A. and Cowled, B.** 2021. Sea lice infestation of salmonids in Chile between 2011 and 2017: Use of regulatory data to describe characteristics and identify risk factors, *Aquaculture*, 530, 2021, 735752,ISSN 0044-8486, https://doi.org/10.1016/j.aquaculture.2020.735752; [5] **Gallardo-Escárate, C., Arriagada, C., Carrera, C., Gonçalves, A.T., Nuñez-Acuña, G., Valenzuela-Miranda, D. and Valenzuela-Muñoz, V.** 2019. The race between host and sea lice in the Chilean salmon farming: a genomic approach. *Reviews in Aquaculture*, 11(2): 325–229. https://doi.org/10.1111/raq.12334; [6] **Lepe-López M, Escobar-Dodero J, Rubio D, Alvarez J, Zimin-Veselkoff N. and Mardones FO** 2021. Epidemiological Factors Associated With Caligus rogercresseyi Infection, Abundance, and Spatial Distribution in Southern Chile. *Frontiers in Veterinary Science,* 8:595024. doi: 10.3389/fvets.2021.595024; [7] **MMA (Ministerio de Medio Ambiente)**. 2020. Ministerio de Medio Ambiente, Chile. Climate Change Risk Maps Aquaculture. https://arclim.mma.gob.cl/atlas/sector_index/acuicultura/ [8] **Figueroa, J., Cárcamo, J., Yañez, A., Olavarria, V., Ruiz, P., Manríquez, R., Muñoz, C., Romero, A. and Avendaño-Herrera, R.** 2019. Addressing viral and bacterial threats to salmon farming in Chile: historical contexts and perspectives for management and control. *Reviews in Aquaculture*, 11: 299–324. https://doi.org/10.1111/raq.12333.

b) Risk components

Hazard (H) here refers to the potential for a physical/biophysical event or phenomenon to cause harm or damage to the system or defined adaptation unit (see Chapter 2 and Table 10 for more information).

Hazards may cause direct harm or may trigger a chain of events that could cause harm, and identifying them requires an understanding of the factors involved and how they could affect aquaculture activities. However, even where the main hazards, factors and chains of events are identified, there are often no reliable available models of their future trajectories under climate change.

In the present case study, the reduction of precipitation due to climate change has been identified as the most relevant forcing factor affecting both salmon farming and mussel farming in the Northern Patagonian marine area where the activities take place (Garreaud *et al*., 2012; Soto *et al*., 2019, 2020, 2021). **Thus, we use the drought projection for the following 50 years as the main hazard, and we explore the chain of events that could affect salmon farming due to reduced precipitation** (Figure 11).

Declines in precipitation have reduced and will continue to reduce freshwater inputs from rivers discharging into fjords, thus causing an increase in the salinity of the fjords (Aguayo *et al.*, 2019) – which, in turn, can promote increased salmon parasitism including by sea lice and gill amoeba (Padrós and Constenla, 2021). However, we do not have a precise quantitative model connecting less precipitation with increased salinity that drives increased parasitism, and for this reason '**reduced precipitation' is considered as a proxy for the immediate hazard of increased parasitism under climate change**.

Figure 11 illustrates the chain of events that could affect salmon farming due to reduced precipitation. The reduction of precipitation is the main climate change forcing factor which can be projected in line with increased GHG pathways and other factors for Southern Chile. Therefore, it is used here as a climate change hazard proxy (IPCC, 2014, 2022), while the chain of events resulting in more favourable conditions for an increase in salmon parasites is the immediate hazard – that is, the condition causing harm to the activity.

Even though parasitism is not a direct cause of mortality in farmed salmon, it can reduce feeding, growth, productivity and general fish health, which in turn can increase mortality due to bacterial and viral diseases. Broadly speaking, an increase in parasitism generates biomass and economic losses (Gallardo-Escarate *et al*., 2019; Soto *et al*., 2019, 2020; risk maps at MMA (2020); https://arclim.mma.gob.cl/atlas/view/acuicultura_f_salmon_para/).

Table 10 presents the climate change risk components for the salmon farms in the 20 SFAs. For each identified risk, a description and indicators are proposed.

FIGURE 11
Chain of events that could affect salmon farming due to reduced precipitation

Exposure (E) represents what can be lost, measured as salmon biomass, by each SFA annually. For this exercise, we used the average salmon production (harvest) of 2017–2018 reported for each SFA.

Sensitivity (S) refers to the degree to which a system can be affected by climate variability due to the natural susceptibility of the ecosystem and of the conditions of aquaculture farming, species, habitats, livelihoods, aquaculture-dependent communities, etc. that make it more prone to be affected. For example, specific hydrological characteristics of areas where fish are farmed, bad management practices which stress fish, or absent or weak biosecurity can all make aquaculture systems more susceptible to being affected. Some of these conditions cannot be modified (e.g. hydrological characteristics), but others, such as farm management, can.

In the current example, sensitivity conditions include:

- **An indicator of 'water age', representing the water retention (the opposite of hydrological turnover) of a fjord or coastal system.** A water body with greater 'age' or lower exchange rate, in general, has less oxygen, accumulates more nutrients, and are a more effective parasites reservoir. All these could facilitate stressful conditions for fish.
- **Current water density (combination of salinity and temperature) as an indicator of sensitivity to reduction in freshwater input.** An environment with low salinity and high river inflow is more sensitive to a reduction in precipitation than a marine environment, whose salinity would not change significantly even with less rain.
- **The accumulated biomass produced in the SFA during the past 10 years is an indicator of the potential accumulation of nutrients (introduced by salmon farming) and the potential reserve/accumulation of diseases and parasites (Soto *et al.*, 2019, 2020).** A long-established SFA will have a higher score than one with a very recent salmon farming history.
- **The dominance of *Salmo salar* is also considered as an indicator of sensitivity, especially with the potential increase of parasites and diseases, since it is the most sensitive species to infections from sea lice (*Caligus rogercresseyi*) and the main bacterial disease SRS (*Piscirickettsia salmonis*).** By contrast, Coho salmon and rainbow trout appear to be more resistant to sea lice and SRS (Gallardo-Escarate *et al*., 2019; Figueroa *et al*., 2019). Thus, a high concentration of *Salmo salar* in the SFA indicates a higher sensitivity to the hazard. Generally, a monoculture farming area will be more sensitive to parasites than one with a more diverse array of species. Here, we use the term 'polyculture' when two or more farmed species share a common water body.
- **Sanitary management is an important sensitivity indicator,** given that fish in better health and welfare will likely be more resilient to parasites and other external stressors. In this instance, we take the level of antimicrobials (AM) used in the previous two production cycles as an indicator/proxy for the sanitary conditions, since bacterial and other diseases are often promoted and facilitated by infestations of sea lice. Therefore, a high use of AM is considered as an indicator of poor sanitary conditions.

Adaptive capacity (AC) refers to all the measures and conditions (including both private and public efforts) that allow the local governance unit to prevent and mitigate hazard impacts.

The ARClim risk assessment and maps did not include adaptive capacity; this component was considered as equal to zero because at the time the risk maps were being developed there was not enough information or comparable indicators to measure AC for all the SFAs. Thus, in the current case study we explore and model some measures and technical innovations, which are mostly being implemented by farmers and salmon farming companies, that reduce risk while not modifying exposure or sensitivity.

Following Aqua-Adapt, below we describe step by step the assessment of the risk of losing farmed salmon biomass due to increased parasitism (Soto *et al*., 2020).

The risk component scores go from 1 to 5, for hazard (H), exposure (E) and vulnerability (Va). Va is represented here by sensitivity (S) and by adaptive capacity (AC). S was estimated with scores set for 5 subcomponents, while AC was defined within a range from 0 to 1.

The hazard score for each SFA was calculated based on estimated climatic projection components for the central latitude of each SFA (using the information described in step 1 above). The hazard values were obtained from the change that the climatic variables will experience between the recent past (1980–2010) and the near future (2035–2065), considering the worst GHG scenario (RCP 8.5). The hazard components included a drought trend index, the number of consecutive days with precipitation, a drought frequency index, and the number of days with temperatures above 25 °C. Climatic projections were generated by the ARClim project, using General Circulation Models (see more at https://arclim.mma.gob.cl/). The descriptions and scoring details used to estimate E, S and AC are shown in Table 10.

The formula to estimate risk is R = E*Va*H, where Va = S*(1-AC), and the final risk value is normalized by dividing by 125 (based on maximum scores of 5 for E, S and H). For each risk component we used several subcomponents/indicators (see Table 10), averaging these out to give the final values for H, E, S and AC (Table 11). The Figure 10 uses colours to represent the five scale comparative risk values.

iv. Step 4. Design an adaptation work plan

As explained above the design of an adaptation strategy is partially ongoing through the NAP for fisheries and aquaculture, therefore a simple modelling was performed.

To assess the potential effect of introducing specific adaptation measures to reduce risks, we modelled a situation where these have been incorporated. Thus, Table 11 describes current conditions (T_0) and a condition in which we have modified components to reduce risks (T_1); risk reduction is estimated as the difference between risk at T_0 and T_1. The symbol T_{1E} corresponds to a reduction of exposure at T_1; T_{1S} corresponds to a reduction of sensitivity at T_1; while T_{1AC} corresponds to an increase of adaptive capacity at T_1. The selection of measures and a detailed explanation of the reduced risk situation is presented in the following step 4 section, on identifying and implementing adaptation measures.

v. Step 4a – Define the adaptation measures

a) Adaptation options and measures to reduce climate change risks for salmon farming

Since climate change-related hazards such as increased parasitism reduce the growth rate of salmon and/or increase their mortality, there is a need for actions to reduce these risks and avoid losses; however, all actions have associated costs. These costs could reduce the profitability of salmon farming, and adaptation measures that avoid these costs can be beneficial to salmon companies from an environmental as well as an economic point of view. However, adaptation measures might have different degrees of effectiveness in avoiding climate change impacts, and different costs associated with their implementation. Thus, it is important to assess the cost-effectiveness of the potential adaptation measures. Moreover, it is necessary to distinguish between public and private costs. Private costs are assumed by individual agents (firms, workers, families,

TABLE 11

Scores for hazard (H), exposure (E), sensitivity (S) (1 to 5) and adaptive capacity (AC) (0 to 1), and estimated risk of losing farmed salmon biomass due to increased parasitism, for 20 SFAs organized from North to South in Los Lagos, Chile

	Hazard (H)	Exposure (E)		Accumulated harvested biomass (2010–2018)	*Salmo salar* monoculture		Fresh water dependency	Sanitary condition		Sealice index		Sensitivity (S)		Adaptation capacity (AC)		Risk base line (T_0) and considering T_{1E} or T_{1S} or T_{1AC}				Risk reduction with individual measures			Risk and reduction with all T_{1E}, T_{1S}, T_{1AC}	
SFA	T_0	T_0	T_{1E}	T_0	T_0	T_1	T_0	T_0	T_1	T_0	T_1	T_0	T_{1S}	T_0	T_{1AC}	T_0	T_{1E}	T_{1S}	T_{1AC}	Exposure reduced	Sensitivity reduced	AC increased	Risk	Risk reduction
1	5	5		5	1		5	3		2		3.2		0.0		0.64								
2	5	5	4	5	4	3	3	5	3	5	3	4.4	3.5	0.0	0,2	0.88	0.70	0.70	0.70	0.18	0.18	0.18	0.45	0.70
3A	5	3		5	1		3	3				3		0.0		0.36								
3B	5	3		5	3		3	4		2		3.4		0.0		0.41								
6	5	5		3	5		3	1		2		2.8		0.0		0.56								
17B	5	3		5	3		4	4		4		4		0.0		0.48								
7	5	3		4	3		2	3		4		3.2		0.0		0.38								
17A	4.8	4		5	5	3	4	5	3	2		4.2	3.4	0.0		0.64		0.52			0.12			
8	5.0	3		5	3		2	4		5		3.8		0.0		0.46								
9A	4.8	4		5	4		2	4		4		3.8		0.0		0.58								
10A	4.5	4		5	4		2	4		4		3.8		0.0		0.55								
9B	4.8	3		3	4		2	4		5		3.6		0.0		0.41								
15	4.8	1		2	5		1	3		3		2.8		0.0		0.11								
16	4.8	3		4	5		3	4		3		3.8		0.0		0.43								
9C	4.8	2		3	5		2	1		3		2.8		0.0		0.21								
10B	4.5	4		4	5		2	5		5		4.2		0.0		0.60								
14	4.8	3		4	5		1	4		3		3.4		0.0		0.39								
11	4.5	5		5	3		2	5		3		3.6		0.0		0.65								
12A	4.3	3		4	3		2	3		4		3.2		0.0		0.33								
12B	4.0	1		2	5		1	3		2		2.6		0.0		0.08								

Note: Score values are described considering current conditions (T_0) for all the SFAs, and at T_1 only for SFAs 2 and 17A where we have modified components to reduce risks. A red colour scale provides a comparative visual assessment of estimated risks from highest (darker red) to lowest (light red, pink to white). Risk is R = E*Va*H, where Va = S*(1-AC). Current farming conditions it is considered as time = 0; and is represented by "T_0" and a condition at a later time in which we have modified components to reduce risks it is represented by "T_1"; risk reduction is estimated as the difference between risk at T_0 and T_1. The symbol T_{1E} corresponds to a reduction of exposure at T_1; T_{1S} corresponds to a reduction of sensitivity at T_1; while T_{1AC} corresponds to an increase of adaptive capacity at T_1.

Risk is R = E*Va*H, where Va = S*(1-AC). Current farming conditions it is considered as time = 0; and is represented by "T_0" and a condition at a later time in which we have modified components to reduce risks it is represented by "T_1"; risk reduction is estimated as the difference between risk at T_0 and T_1. The symbol T_{1E} corresponds to a reduction of exposure at T_1; T_{1S} corresponds to a reduction of sensitivity at T_1; while T_{1AC} corresponds to an increase of adaptive capacity at T_1.

AC = adaptive capacity.

communities, municipalities), while social costs refer to the total costs assumed by the government and society at large. Private costs might be financed by the individual agents themselves, or with partial or total support from the government or other entities.

To discuss different adaptation measures, we will divide them into measures that **decrease exposure** to the hazard, measures that **reduce sensitivity**, and measures that **increase the adaptive capacity**. Measures that reduce sensitivity and increase adaptive capacity can be considered as measures that improve **resilience.** As mentioned above, the salmon and mussel farming risk maps did not include AC; however, in the case studies described here, we model the adoption of measures including some AC indicators in the comparison of risks under current conditions (T_0) and at T_1, as described in Table 11.

As discussed in the main text of Aqua-Adapt (Chapter 2), different measures and options may have different timings depending on the implementation context; this is a core element of the planning process.

For the case study, we consider the following adaptation actions to reduce risks:

b) Reduce exposure (E)

Reduce E by reducing farming biomass in areas with higher risk. This could mean moving biomass from a given farming area(s) to another farming area(s) with lower risks within the same region or reducing total salmon production across the entire Los Lagos region, which may then result in moving biomass to another region.

In the current analysis, as discussed, we only address adaptation options for 20 SFAs in the Northern part of the Los Lagos region (Figure 9), since these are the SFAs that are most likely to experience the largest hazard (drought) and show the largest exposure.

In this analysis, we simulate what happens if the intervention reduces salmon biomass in one of the SFAs with the highest production. This type of measure must be implemented by the government using compulsory or non-compulsory, but effective, regulatory tools and is assumed to affect all individual farmers/companies holding farming licences in the specific SFA that is required to reduce biomass.

In addition, this type of measure bears costs for different stakeholder groups. For the government it involves developing regulations to implement the measure and putting in place monitoring and auditing systems. For farmers it might involve relocation costs, plus a reduction in productivity and profitability to the extent that they might need to change previous production planning. For workers and communities, it might bring a loss of income as the level of activity in the affected farms is reduced. All these costs will depend on the intensity and duration of the measures and the adaptive capacity of the different stakeholders, and they will vary geographically.

c) Reduce sensitivity (S)

Reduce S by improving biosecurity measures, for example by developing and using vaccines against parasites and/or immune enhancers that make fish more resistant to parasites.

This measure will generally be adopted by individual farmers, and their individual farms will benefit from its effectiveness in reducing risk. By the same token, the direct costs of implementation will mainly be borne by the farmers. However, if all the farmers in an affected SFA adopt these measures there will be a reduction of risk across the whole SFA, and this is an assumption we consider in our analysis.

A measure such as the use of vaccines in essence protects vaccinated fish while the effect on the overall parasite population remains unknown; however, the use of vaccines against sea lice remains a possibility, as active research is in progress (Gallardo-Escárate *et al*., 2019; Johny *et al*., 2024).

Other measures often used to control diseases such as AM can also have some undesired effects specially when there is excessive use, such as generating AM resistance and affecting ecosystem processes. Therefore, the use of chemicals potentially harmful for the ecosystem are less recommended to reduce sensitivity.

Another biosecurity measure to reduce the impact of sea lice is the management of the timing at which young fish enter the fattening stage in the marine farms: in this case, the government will play a key role by coordinating joint actions by different farms in each SFA. This measure can also have associated private costs or benefits to the extent that it can positively or negatively affect the productivity of the fattening cycle. We chose to consider this measure under adaptive capacity (see below).

The implementation of polyculture is another adaptation measure that reduces sensitivity. The idea is to farm different salmon species in the same area, instead of concentrating production in a single species. Since different species have different levels of sensitivity to some types of hazards, such as the pathogens that can develop with climate change, then when they are cultivated together the impact of a pathogen on one species could be modulated by the lower sensitivity of the other species. This could be especially important in the Chilean salmon industry, which is heavily concentrated on the production of Atlantic salmon – a species which is especially sensitive to some of the more common parasitic pathogens existing in Los Lagos. This measure will essentially be coordinated by government and facilitated through incentives to change the farmed species which will likely involve internal adjustment costs for the farms, since implementing it will involve changes in production planning and will probably influence production costs and income, since different species have diverse cycle lengths, costs of production, mortality and morbidity rates, sizes and market prices, along with other factors that affect the economic performance of the farms. There are, however, no important costs for other stakeholders.

d) Increase adaptive capacity (AC)

Increase the AC can be done by changing growing and harvesting times, as well as the specific time of stocking in the marine sites, without reducing total harvest and production. This is possible by modifying the production cycle reducing the time salmon farming fattening occurs in marine cages; that is, increasing the time span that fish spend in freshwater land-based farms beyond the smolting size.

This can be achieved with two complementary measures: by selecting strains that grow faster and can spend more time in freshwater, and by improving land-based facilities and conditions.[8] If this measure is implemented using existing infrastructure and personnel, additional costs will probably be low. However, if it is necessary to invest in research into faster-growing strains, or to make investments in land-based facilities, costs may initially be higher. Either way, most or all of the costs for this measure will be borne by the farmers. Therefore, we distinguish between two forms of implementation: a short-term low-cost option, based on existing infrastructure and knowledge; and a long-term high-cost option, involving research and investments in land-based facilities.

Risk response to adaptation measures in two salmon farming areas: SFA 2 and SFA 17A

Here we describe how risk components are estimated for the risk maps (ARClim, Soto *et al.*, 2020) in the 20 SFAs located in the Los Lagos region, and analyse changes resulting from different adaptation measures in a pair of SFAs which show the highest

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[8] The development of inland aquaculture through recirculating aquaculture systems (RAS) can be seen as an measure that reduces the duration of the saltwater fattening process for salmon. This is a high-cost alternative which involves costs for different stakeholders.

risks (Table 11, risk baseline $\mathbf{T}_0$ vs risk at $\mathbf{T}_1$ including adaptation measures). All SFAs confront a varying drought hazard that is high in Los Lagos SFAs compared with the southernmost SFAs (Figure 9); on a scale from 1 (very low) to 5 (very high), the magnitude of the hazard (drought in this case) varies across SFAs between 4.0 and 5.0 (Table 11). While we cannot modify the climate change hazard, we introduce changes that can take place at $\mathbf{T}_1$ affecting exposure (*E*) and vulnerability (*Va*) by modifying components of the latter, namely sensitivity (*S*) and adaptive capacity (AC), and calculating the potential risk reduction of these measures. Below we model changes for different scenarios in SFA 2 and SFA 17A.

SFA 2 shows the highest level of hazard (5), has the highest level of exposure (5), and shows the highest level of sensitivity (4.4) of the 20 SFAs in our sample. So, in the baseline situation it presents the highest risk among any of them. Then we simulate various adaptation measures. First, we assume that SFA 2 reduces its exposure from a current (T_0) score value of 5 to a value of 4 at T_1 and estimate the risk reduction impact of this measure.[9] Second, we introduce several changes to the sensitivity subcomponents (Table 11, orange-headed columns), leaving us with values for T_{S0} and reduced values at T_{S1}. Here we assume that for SFA 2 we can reduce the monoculture of *S. salar* (thus moving from 4 at T_0 to 3 at T_1, Table 11) by increasing the production of rainbow trout and/or of Coho salmon. The sensitivity index is reduced from 4.3 to 3.5. We also reduce poor sanitary conditions (from 5 to 3) by introducing vaccination for diseases and, if possible, for sea lice (Johny *et al.*, 2024). We could also increase the use of immune stimulants to increase fish health and welfare. Third, we introduce an improvement in adaptive capacity, which we have considered equal to zero at T_0, by modifying growing and harvesting times without reducing total harvest and production (see Chapter 2). Modifying the time fish spend in the marine environment aims to reduce their chances of experiencing higher temperatures and of avoiding the peaks of sea lice infestations. Keeping young fish beyond the smolting stage in better controlled inland facilities or RAS systems reduces the period during which they will experience hazards and impacts in the sea. As they do finally move to sea cages and reach the expected harvest size in the 'adaptation unit area' without changes in projected production, we do not consider this as a reduction in exposure but rather as an increase in adaptive capacity. As shown in Table 11, an increase of AC from 0 to 0.2 generates a risk reduction of 0.18 points.

Note that the impact of the different adaptation measures has been considered in such a way that, in each case, the risk is reduced by the same amount – that is, from the original risk value of 0.88 before any measure takes place, it is reduced in all cases to 0.70. Thus, the reduction in total risk is 0.18 points for each individual measure (Table 11). This result, of equal reduction in risk for all different measures, of course, does not necessarily have to happen. In this case, we have worked out in this way to simplify the cost-effectiveness analysis. With this approach, what makes the difference between the measures is the implementation costs.

Table 11 also highlights the case of SFA 17A, where at T_1 we reduce the score values for some sensitivity components; namely reducing *S. salar* monoculture (from 5 to 3) and reducing poor sanitary conditions (from 5 to 3). The average S values are then reduced from 4.2 to 3.4 and the risk goes from 0.64 to 0.52, with a 0.12 point reduction. In this case the total biomass farmed is maintained. The 0.12 point reduction in risk is smaller than in the SFA 2 case, and the principal reason for this difference appears to be the difference in the initial risk situation. In this specific case, the hazard and the exposure are greater in SFA 2 than SFA 17 at the base situation (T_0), meaning that when changes of a similar magnitude are introduced in both cases they have a higher impact

[9] This change in the score value implies reducing production in this SFA2 area from 61 200 tonnes (average 2017-2018) to 30 000 or less.

in the first one (Table 11). This reflects the cumulative (multiplicative) nature of this way of measuring risk, which means that all components must be evaluated to obtain a general assessment of the impact of changes in different components of risk.

It should also be noted that the risk reduction is estimated for each of the adaptation measures independently. Furthermore, if we can introduce the three measures together, then the risk value will fall from 0.88 at T_0 to 0.45 at T_1, a reduction of 0.70 points – this would be a great improvement (Table 11).

vi. Step 4b – Applying a cost-effectiveness analysis

Through the application of a basic conceptual model for the cost-effectiveness analysis, we assess and compare adaptation actions by using the cost per unit of impact (e.g. the effect caused by the action). In the simple modelling proposed here we estimate the effectiveness of each measure independently, in terms of risk reduction (Table 12). Then we use cost component scores by stakeholder group and according to adaptation categories and adaptation actions. The process can easily be extended to consider cost estimates in a situation with rich data/information and the potential synergies that could be achieved by joint implementation of some or all of the adaptation actions previously described.

To implement our case study, we consider the following:

- Let a denote an adaptation activity or action to reduce fish parasite risk resulting from a reduction in precipitation that increases salinity and facilitates or promotes fish parasites. The analysis considers the implementation of a given action in an SFA. Since all the measures considered here bear some cost, we assume that they are usually implemented in SFAs with higher risks.
- Let e represent the effect or consequence of the adaptation action, so that e is a function of a, with which we write $e(a)$ (the reduction/change in risk).
- Also, let us denote base risk as R_o and the reduction in risk due to an adaptation action as $(R_o - R_1)$, where R_1 is the risk level after the implementation of the adaptation action, with $R_o > R_1$ if the adaptation action is effective.

The analysis is performed using a semi-quantitative risk assessment. The model combines the exposure of the biological production (E), which is the harvested biomass that could be lost or affected due to a hazard, with the vulnerability (Va) of the unit of analysis to the hazard (H). As previously described in the conceptual framework, vulnerability refers to the degree to which a system is susceptible to, and/or unable to cope with, adverse effects of climate change.

A base risk value was estimated for each of the 20 SFAs in Los Lagos.

$$\text{Base risk} = R_o = E_o \times Va_o \times H$$

Vulnerability (Va) includes the severity of the impact and the ability to recover; it therefore has two components, namely sensitivity (S) and adaptive capacity (AC). Specifically, we consider $Va_o = S_o \text{ x } (1- AC_o)$. (Our analysis scores each risk component from 1 to 5, where 1 represents the minimum level and 5 represents the highest level; we also normalize the resulting base risk so that it fits into the range (0 to 1); with 0 and 1 representing minimum and maximum risk, respectively.)

In this setting, the effect of an adaptation action could be transmitted to risk by affecting either exposure (Eo), vulnerability (Va_o), or both. We also notice that the effect of changes in vulnerability due to an adaptation action would be transmitted through sensitivity (S_o), or adaptive capacity (AC_o), or both. Consequently, if the adaptation action affects exposure and adaptive capacity, the risk after implementation is given by:

$R_1 = E_1 \times Va_1 \times H$, and

$e = R_o - R_1 = (E_o \times Va_o - E_1 \times Va_1) \times H,$

where *e* denotes the change in risk because of the measure implemented. Note that if the adaptation action only affects exposure, then the effect of the action is given by:

$e' = R_o - R_1 = (E_o - E_1) \times Va_o \times H$

Similarly, if the adaptation action only affects vulnerability, the effect of the action is given by:

$e'' = R_o - R_1 = (Va_o - Va_1) \times E_o \times H$

Where the difference in vulnerability could be the result of the impact from the adaptation action on sensitivity, adaptive capacity, or both.

Table 11 describes the scores for each risk component (*H*, *E*, *S* and *AC*) to estimate the risks of losing salmon biomass due to increased parasitism. Values are estimated considering the current salmon farming management situation (T_0) and the estimated risk situation at T_1 when some of the risk components have been modified to reduce total risk. It also describes the modifications to *E* and *S* and to *AC*.

The implementation of an adaptation action is costly as it demands resources. As explained above we need to calculate the cost associated with the implementation of each adaptation action to be able to compute their cost-effectiveness.

The cost-effectiveness is calculated as: $C\text{-}E = c(a)/e(a)$.

Based on a qualitative analysis, we identify the cost for each action *c*(*a*) using a scale that identifies three levels of costs: High (3), Medium (2), and Low (1) (Table 12). Of course, the scale could be modified to include more variability – but since the social costs associated with risk-reducing measures are often unknown or difficult to calculate accurately, it is useful to work with a coarse scale where what matters is the general order of magnitude of the costs rather than specific cost estimations.

There are different ways of estimating the costs associated with different adaptation measures. Knowledge of the cost structure of the farms over the production cycle would make possible to estimate the different costs items affected by the measures and then from this information calculate the impact that these measures could have on the total production costs per kilogram of farmed salmon. This would make possible to compare the costs of different measures. This knowledge, in principle, could be gathered through interviews, surveys or focus group discussions. However, this procedure is quite time demanding and requires consent from the farmers and or firms to share sensible information. Moreover, this procedure only collects private cost information related to individual farmers and/or firms but does not offer access to other cost information relevant for assessing the social costs of the adaptation measures. These are, the costs for the government, costs for other private stakeholders, and social external costs. Such omission is quite important when one aims to calculate the costs for the society of different adaptation measures.

Here we use a coarser way of assessing the costs of the different adaptation measures. We based our estimated costs on information obtained from different sources and of different quality: gross cost estimates obtained from diverse sources (scientific and technical papers, opinions in press articles, conversations with industrial managers and experts). We sorted and catalogued the costs of different adaptation

TABLE 12
Semiquantitative estimation of effectiveness, costs, and cost-effectiveness (C/E) for some of the adaptation measures proposed here to reduce salmon farming risks under climate change

	Adaptation action	Effectiveness	Farmers costs (for individual farmers)	Farmers C/E*	Government costs	Government C/E	Cost for other stakeholders within the salmon value chain	Average cost (score)	Overall C/E (Av Cost/Eff)
Reduce exposure	Reduce farming biomass in SFA with higher risk	2	2	1	2	1	2	2	1
Reduce sensitivity	Implementing biosecurity measures	2	1	0.5	1	0.5		1	0.5
	Implement polyculture areas	2	2	1	1	0.5		1,5	0.75
Increase adaptive capacity	Modify growing and harvesting times (low cost)	2	1	0.5	1	0.5		1	0.5
	All of the above	3	3	1	1.25	0.4	1	1.8	0.6
	Moving farms to RAS on land	3	3	1	1	0.3	2	2.0	0.7
			Maximum C/E = 3		Minimum C/E = 0.3				

Note: Costs and effectiveness are estimated as High (3), Medium (2) and Low (1). Effectiveness of the measures is considered as Low equivalent to 1 when points in risk reduction are < 0.15 (see Table 11); Medium 2= 0.16 - 0.50; and High 3 = > 0.50. We do not include here costs for other stakeholders outside the salmon value chain who may also be affected by the adaptation measure, such as artisanal fishers, tourism companies, etc.

* Farmer cost-effectiveness (C/E) is calculated as c(a)/e(a), where c(a) is the cost indicator and e(a) is effectiveness. Thus, the minimum value of the cost-effectiveness index is 0.33 (combination of lowest cost and highest effectiveness, that is 1:3), which is comparatively the best option (bright green); while the maximum value of the cost-effectiveness index is 3 (combination of highest cost and lowest effectiveness, that is 3:1) which is the worst option (bright red). In the present case the worst comparative value for C/E is 1 (light orange color).

RAS = recirculating aquaculture systems; SFA = salmon farming concession areas.

measures for different stakeholders, including all types of social costs, and categorized them as High, Medium or Low. The High costs correspond to costs that involve very large and time-consuming investments that would bring about a major change in production conditions and that imply large adaptation measures. The Medium costs are costs that may significantly affect the results of the activity, but that can be adopted within the current organization of the farm and sector/industry. Finally, low costs are for measures that entail some minor costs to some stakeholders, but that do not significantly alter the current organization, or the results obtained.

In Table 12, we describe the results of the cost-effectiveness analysis representing three levels for effectivity: High (3), Medium (2), and Low (1), considering the risk reduction points (Table 11), and three levels for costs: High (3), Medium (2), and Low (1). This offers a visual comparison between effectiveness and costs (of course, as indicated previously, with better information the scale could be modified to include more variability). The levels of effectiveness were allocated by the research team preparing this document, based on the effectivity analysis (risk reduction). Similarly, the levels of costs were allocated based on the cost analysis described above. The results are presented for each adaptation strategy and action discussed above. Since, in our exercise, all measures have the same impact on the expected risk (0.2 reduction in the risk scale), which is the measure of effectiveness in our framework, this means that the ordering of the cost-effectiveness analysis will be the same as for the cost analyses. In other words, the order of the options c(a)/e(a), is the same as the c(a), since the denominator is the same in all cases in the effectiveness analysis.

As we can see in Table 12, the cost impact of each action differs between stakeholder categories. We have chosen to discriminate between private farmers, government, and other private stakeholders such as workers, communities and social organizations related to the salmon farming value chain. The distinction is important because alternative actions can be equivalent from a cost perspective for the same stakeholder but can vary between different stakeholder groups. For instance, for farmers the costs of reducing biomass in the areas with higher risk, implementing biosecurity measures, and modifying growing and harvesting times, are broadly equivalent. However, these measures are not equivalent from the perspective of other stakeholders. Specifically, while the second and third measures do not seem to entail noteworthy additional costs to the government and other private stakeholders, the first one does, because this measure will likely reduce jobs along the whole value chain. So, from their perspective, these alternatives are not equivalent from a cost perspective, and therefore they shouldn´t be equivalent from a broad social viewpoint. To have a measure of the total social cost we add the cost-effectiveness values and divide them by the number of different stakeholders (Table 12).

Another point worth mentioning is that some measures affect a range of different stakeholders, while others mainly affect farmers.[10] In the first case, some of the additional costs derive from the coordination of different stakeholders required to implement the measure, while in the second case this coordination is not required since the farmers can act independently. This clearly simplifies the implementation of the measure, and is an argument to, given equivalence in all other aspects, prefer this type of measures.

From the perspective of the cost-effectiveness analysis, the preferred actions correspond to measures that have recently been implemented by salmon farmers in Chile. They are trying to control parasitism (whether or not it is driven by climate change) by implementing diverse biosecurity measures, and they are also modifying growing and harvesting times. According to our analysis, these are cost-effective measures. However, these are short-term measures that do not require major changes to the production process. The question is whether they will be sufficient to meet all the challenges posed by climate change.

Table 12 indicates that improving biosecurity measures and modifying the time that fish spend in the marine environment are the most cost-effective measures in our exercise. We can also compare cost-effectiveness for a given action across stakeholders, and where the value of the index is lower, it implies that the action is preferable from a cost-effectiveness perspective.

One interesting example is the innovative technologies being implemented by farmers to reduce the risk of losing biomass due to HABs or hypoxic events (Box 2). In these cases, relatively low-cost measures could be more effective in reducing risk than higher-cost measures such as moving farms (reducing exposure). However, the effectiveness of such technologies must still be proved.

vii. Steps 5 and 6: Implementation, monitoring and evaluation of the strategy

We did not perform an implementation strategy because it would have required a participatory process, a full economic evaluation and assessment of potential social and environmental implications. Currently one of the most complex issues is the governance implication of re arrangement of space for salmon farming in Chile considering climate change risks for the sector and risks posed by this sector to natural ecosystems under climate change scenarios (Soto *et al*., 2021; Engler, 2024)

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[10] Generally, all measures require the intervention of the government or the regulatory authorities. As long as these measures can be implemented with the existing legislation and range of existing instruments, the additional costs of implementing the measures are considered to be negligible. The government costs increase when implementation of additional measures require new legal or material instruments.

BOX 2

Innovative technologies

Regarding adaptive capacity (AC), the salmon farming sector has already improved and strengthened some AC measures, such as the implementation of sophisticated environmental monitoring and early warning systems for climate change-related hazards such as harmful algal blooms (HAB). The ARClim risk maps included HABs as a relevant hazard (Soto *et al*., 2020) and some measures were recommended to reduce risks including reducing exposure and improving AC. In fact, after the risk maps were made publicly available at the end of 2020, in March 2021 there was an HAB event in one of the SFAs which had already been identified as having higher risk (Soto *et al*., 2021) which resulted in severe losses for the salmon production. The risk maps and analysis had recommended reducing salmon farming biomass in areas with higher HAB risks, but no action was taken. Currently, rather than reducing exposure, in addition to early warning and monitoring systems, other specific AC measures involving technological innovation are in use. One is to produce microbubbles (see more at https://www.fishfarmingexpert.com/aeration-discs-low-o2-microbubble-curtains/chilean-microbubble-company-on-the-rise-in-scotland/1727300) under salmon cages which may be exposed to HAB, thus creating a kind of bubble curtain around the farm and moving bottom water without the toxic algae to dilute their effect on the fish. The systems have not yet been fully tested against HABs and they can be costly, but the investment may be worthwhile given the cost to farmers of reducing production in some of their sites. Similar technologies but with nanobubbles (Yaparatne *et al.,* 2024) are also being adopted to combat hypoxic events; however, more field tests under production conditions are needed, and farmers need to be given better information. Nevertheless, technological innovation and artificial inteligence systems are undoubtedly offering new options for adaptation to climatic variability and climate change trends. The most important advice to farmers is to ensure that appropriate information is available to make optimal decisions on the basis of costs and effectiveness.

Note: **Soto, D., León-Muñoz, J., Molinet, C., Soria-Galvarro, Y., Videla, J., Opazo, D., Díaz, P., Tapia, F. and Segura, C. 2020.** *Informe Proyecto ARClim: Acuicultura*. https://arclim.mma.gob.cl/media/informes_consolidados/01_ACUICULTURA.pdf; **Soto, D., León-Muñoz, J., Garreaud, R., Quiñones, R.A. and Morey, F. 2021.** Scientific warnings could help to reduce farmed salmon mortality due to harmful algal blooms. *Marine Policy*, 132: 104705. https://doi.org/10.1016/j.marpol.2021.104705; **Yaparatne, S., Morón-López, J., Bouchard, D., Garcia-Segura, S. and Apul, O.G.** 2024. Nanobubble applications in aquaculture industry for improving harvest yield, wastewater treatment, and disease control. Science of The Total Environment, 931, 172687, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2024.172687.

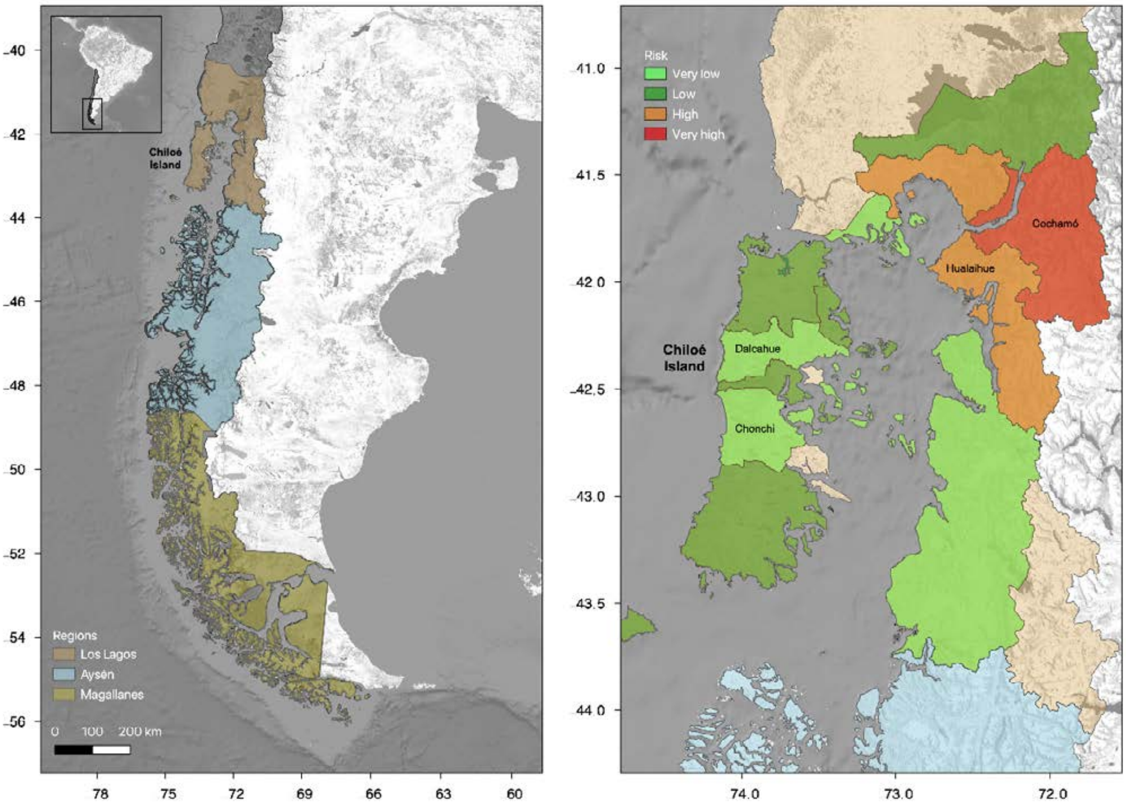
III. DESIGNING AN ADAPTATION STRATEGY FOR CHILEAN MUSSEL SEED PRODUCTION USING AQUA-ADAPT

As in the salmon case study, here we use the opportunity provided by the development of climate change risk maps for aquaculture under the ARClim platform promoted by the Chilean Ministry of Environment (MMA, 2020, https://arclim.mma.gob.cl/atlas/view/acuicultura_mejillones_semilla/). Below we describe Aqua-Adapt process, including the estimation of risks for the collection and production of mussel seed. The comparative risk values are shown in Figure 12.

Farmed mussel production in Chile heavily depends on seed collection from the wild and thus, the farming cycle consists of three main stages: first, capture of seed produced by wild mussel beds, on spatfall ropes; second, seed growth out on the ropes and; third, the growth out or fattening stage to reach commercial size which normally takes place further Southwest from the seed collection stage (Molinet *et al.,* 2015). Seed availability, is sensible to environmental conditions which can consequently affect annual farmed mussel production (Soto *et al*., 2020).

FIGURE 12

Comparative risks of losing wild mussel seed for communes where mussel seed collection takes place in the Los Lagos region, Chile. Colours are over the land area of the communes because the marine division of communes is more difficult to represent



Note: Refer to the disclaimer on page [ii] for the names and boundaries used in this map.

Source: Adapted from **Soto, D., León-Muñoz, J., Molinet, C., Soria-Galvarro, Y., Videla, J., Opazo, D., Díaz, P., Tapia, F. and Segura, C.** 2020. *Informe Proyecto ARClim: Acuicultura*. https://arclim.mma.gob.cl/media/informes_consolidados/01_ACUICULTURA.pdf

Mussel seed collection and mussel growth, in Chile, are both developed almost exclusively in the Los Lagos region (Figure 12). Collection and production of seed is authorized legally through three marine space use mechanisms: i) territorial use rights for fisheries; ii) aquaculture concessions managed by individuals who hold those concessions; and iii) short-term use permits granted to individuals or legal entities by the Maritime Authority.

i. Step 1 – Define the adaptation unit for mussel farming

Risk assessment was carried out for both mussel seed collection (capture-based aquaculture) and for the growing/fattening stage; however, for the present case study we only use climate change risks for the wild seed collection. Adaptation units were the marine areas for each municipality or commune in the Los Lagos region where mussel seed collection takes place (Figure 12). We chose communes because this is the level at which the information on seed capture and production is provided and reported by farmers to the Senarpesca.

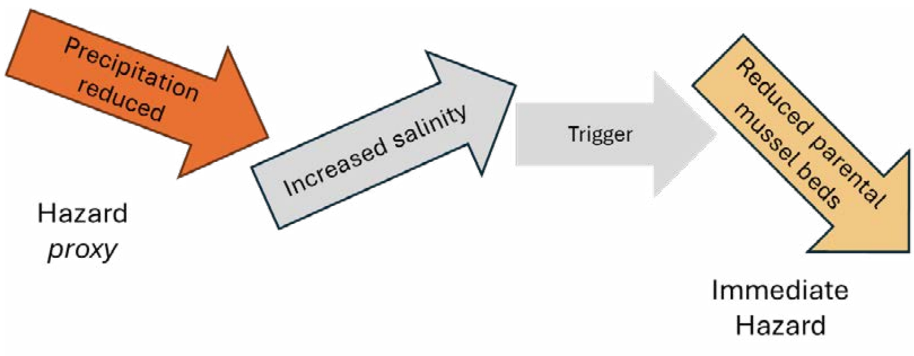
Step 2 is similar to the one described above for salmon farming.

ii. Step 3 – Perform a risk and/or vulnerability assessment on the defined aquaculture adaptation unit

As in the salmon case study we estimated risk as: R = E*Va*H, where Va = S*(1-AC)

Hazard (H). A reduction in precipitation in Northern Patagonia, especially in the fjords where the largest mussel seed harvest takes place (Soto *et al.*, 2020), would

FIGURE 13
Chain of events that could affect mussel production due to reduced precipitation



result in lower freshwater input from rivers feeding the fjords (Aguayo *et al*., 2019). This would produce an environment with greater salinity which would facilitate the presence of less freshwater-tolerant species that compete for space with or predate on mussels (Molinet *et al*., 2015; Molinet *et al*., 2025). Less freshwater would also generate a discontinuity in the density of the water column known as a pycnocline, which separates the freshwater from the deeper, saltier water (León-Muñoz *et al*., 2024). This discontinuity would be relevant for the mobilization and accumulation of the larvae, diminishing their capture in the collecting ropes (Soto *et al*., 2020; Molinet *et al*., 2021). Therefore, the reduction of parental mussel beds (that produce mussel seed) under more saline conditions and the reduction of the pycnocline would be the **immediate hazard** (Figure 13, Table 13) for mussel seed collection and production.

Reduction of precipitation is also the main climate change forcing factor in the case of mussel farming seed collection, and it is used here as a climate change hazard proxy. The increase of water salinity and the thinning of the pycnocline are likely to reduce the mussel beds that produce seed, which is the immediate hazard (e.g. the condition causing harm to the activity).

Exposure (E) represents what can be lost, measured as **mussel seed production**, involving seed capture or collection, and growing of seed to the size ready for fattening. For this exercise we considered the average seed production of 2017–2018 reported for 14 coastal communal waters as the base situation (Figure 12, Table 13).

Sensitivity (S) refers to non-climate-change-related factors (but that can be related to natural variability) that make seed loss more likely. In this case, they include: i) freshwater dependency; ii) poor management of seed collector systems; and iii) fishing pressure on mussel beds by excessive collection of their larvae (Table 13).

Note: The assessment of risk and adaptation options for mussel seed production is quite different from salmon farming, since it involves the capture of wild seed. This is, according to FAO (2011), capture-based aquaculture, defined as the practice of collecting live material from the wild and using it under aquaculture conditions. This practice is common in many aquaculture systems, e.g. in the production of the shrimp (*Penaeus monodon*) (Abdullah *et al*., 2017) and the farming of mud crab (*Scylla serrata*) in Asia (Ramhan *et al*., 2017). In both cases culture-based aquaculture has significant social benefits for local communities, and is an activity that connects fisheries with aquaculture. Adapting it to climate change requires an integrated perspective and with an ecosystem approach FAO (2010).

TABLE 13
Climate change risk components – hazard (H), exposure (E), and sensitivity (S) – and the indicators and scores used in each case, for estimating risks to mussel seed production in Chile

	Description	Indicators	Comments/ assumptions
Hazard (H)	**Reduction of precipitation resulting in a chain of events and effects**	**H value is a composite of several indicators (simple average) described below**	
Climate change driven chain of events affecting mussel seed collection	Less freshwater entering fjords and inner seas results in increased salinity and reduced pycnocline, which can enhance the expansion of species that can displace *M chilensis,* thus reducing parental mussel beds. Also, a reduction in the pycnocline could reduce the concentration of mussel larvae around mussel collectors	Projected number of dry days/ expected drought frequency index scored from 1(lowest) to 5 (highest) (Soto *et al*., 2020[1], 2021[2])	There are no straightforward models directly connecting precipitation with mussel seed production, but there is information connecting lower salinity with healthier, more extensive mussel beds. The salinity gradient plays an important role in structuring the community associated with *M. chilensis*, where this species is confined to a narrow habitat that is bordered by physical-chemical restrictions towards the upper boundary, and predation (Molinet *et al*., 2015[3])
Exposure (E)	Mussel seed biomass that could be lost within the marine area of each commune	We used the average for total seed collected and grown for the period 2015–2018 for each commune* Harvested biomass was scored from 1 (lowest) to 5 (highest)	Most seed collection takes place in fjord systems. Small-scale producers could be the most affected by the loss of mussel beds (Molinet *et al*., 2017[4]). Seeds produced in hatcheries have been proposed as an alternative
Sensitivity, mussels (S_M)	**All (no- CC related) factors that could make the mussel seed loss greater**	**Final S value it is a composite of several indicators (simple average) described below (S_M1 to S_M3)**	
S1 – Freshwater input dependency	Current/normal freshwater influence affecting salinity and pycnocline in fjords and inlets. *M chilensis* beds are better adapted to lower salinities	Current water density (altough representing the temperature and salinity influence of freshwater inputs, salinity was the more variable and influencing factor) scored between 1 (lowest) and 5 (highest)	There is a positive relationship between lower water salinity and optimal mussel bed distribution and conditions (Molinet *et al*., 2015)[3]
S2 – Poor collection and harvesting of seeds	Harvesting systems lose a large proportion of settled seeds before they are harvested them. Such seeds are also considered lost for the wild mussel beds	Values were scored from 1 to 5, representing lowest to largest estimated losses in the harvest of seeds (Soto *et al*., 2020)[1]	More efficient systems that retain most seeds require fewer larvae and could avoid overharvesting
S3 – Poor condition of mussel beds (e.g. due to overexploitation)	Areas (by commune) with mussel beds in good condition, not showing signs of overexploitation and/or other stressors, could provide more and better mussel seeds	Mussel beds were assessed against a deterioration indicator. Values were scored between 1 to 5; with 1 representing excellent wellbeing (e.g. mussel bed growing) and 5 representing an extremely poor and/or overexploited condition (Soto *et al*., 2020)[1]	There is not a straightforward relationship between harvested seed and parental mussel beds. Molinet *et al*. (2015[3], 2017[4]) suggest that seed harvest has a negative impact on mussel beds due to millions of ropes collecting larvae installed in Reloncaví fjord

TABLE 13 (CONTINUED)

	Description	Indicators	Comments/ assumptions
Adaptive capacity (AC)	For the described risk maps the adaptive capacity was considered = 0 (Soto *et al.*, 2020), since there was not enough information on specific measures to assess and compare the different areas. However, for the present exercise we propose some measures and technical innovations that allow risks to be reduced while not modifying exposure or sensitivity	For both salmon farming and mussel farming we use a simple increase in AC consisting in the implementation of environmental monitoring systems. However other examples of AC are also offered to complement case studies	

Production information has been provided by the national fishery service (Senarpesca) and we used the farming concession area per commune.

Note: [1]**Soto, D., León-Muñoz, J., Molinet, C., Soria-Galvarro, Y., Videla, J., Opazo, D., Díaz, P., Tapia, F. and Segura, C.** 2020. Informe Proyecto ARClim: Acuicultura. https://arclim.mma.gob.cl/media/informes_consolidados/01_ACUICULTURA.pdf; [2]**Soto, D., León-Muñoz, J., Garreaud, R., Quiñones, R.A. and Morey, F.** 2021. Scientific warnings could help to reduce farmed salmon mortality due to harmful algal blooms. *Marine Policy*, 132: 104705. https://doi.org/10.1016/j.marpol.2021.104705; [3]**Molinet, C.A., Díaz, M. Arriagada, CB., Cares, L., Marín, S., Astorga, M., and Niklitschek, E.** 2015. Spatial distribution pattern of Mytilus chilensis beds in the Reloncaví fjord: hypothesis on associated processes. *Revista Chilena de Historia Natural*, 88, 1-12. https://dx.doi.org/10.1186/S40693-015-0041-7; [4]**Molinet, C., Díaz, M., Marín, S.L., Astorga, M.P., Ojeda, M., Cares, L. and Asencio, E.** 2017. Relation of mussel spatfall on natural and artificial substrates: Analysis of ecological implications ensuring long-term success and sustainability for mussel farming. *Aquaculture*, 467: 211–218. https://doi.org/10.1016/j.aquaculture.2016.09.019

The components of risk for mussel seed production are described in Table 13, while scoring and estimated baseline risk (with T_0 showing the current situation) for each commune are described in Table 14 and Figure 12 shows the spatial distribution of risks. Both the Figure 11 and the Table 14 show higher risk values for Cochamo, a commune with the largest production of seed (exposure = 5), and very exposed to the hazard (5) since it is highly influenced by freshwater input which is likely to be reduced by climate change. Sensitivity is also the highest in this commune (4.67).

iii. Step 4 – Desing an adaptation work plan

As in the case of salmon farming, here we attempt to modify risk components which can be manipulated. We cannot change the hazard, but we can reduce exposure, sensitivity and increase adaptive capacity.

Reducing exposure in the highest-risk communes of Cochamó (0.93), Puerto Montt and Hualaihue (both 0.59) (Table 14) may not be easy, because these are the areas where the best seed-producing mussel beds are found. However, in the modelling exercise (Table 14) we reduce seed production in Cochamó from approximately 17 000 tonnes (average 2016–2017) with a score of 5, to 10 000 tonnes with a score of 4. Yet, in order not to reduce total seed production, and to retain farmers' access to enough seed to sustain the whole Chilean farmed mussel sector, we must increase seed production by 6 000 tonnes in other low-risk communes. Thus, in the modelling we increase seed production in the communes of Dalcahue and Chonchi by about 3 000 tonnes in each case (Table 14); hence their exposure score goes up to 2 with only a slight increase in risk, which remains low. However, this assumes that the mussel beds in the two communes can support the expected increase in seed production. Furthermore, reducing the seed harvest in Cochamó will have an impact on local small-scale aquaculture operations, and the social impact of this measure must be evaluated.

Other ways of **reducing sensitivity** may be more suitable. For example, recent research indicates that it may be possible to improve the condition of mussel beds in Cochamó by restocking and protecting some of them. We describe this measure as a 'mussel beds conservation programme' in Table 15. It is also possible to improve seed collection to reduce on-site seed losses before harvesting. By reducing seed losses farmers will put

TABLE 14
Risk component scores (from 1 to 5) and estimated risk of losing mussel seed for mussel farming in 14 communes organized from North to South in the Los Lagos region, Chile (Figure 12)

	Hazard (H)	Exposure (E)		Poor mussel bed condition		Fresh water dependency	Poor seed managment		Sensitivity (S)		Adaptive capacity (AC)		Risk base line (T_0) and considering T_{1E} or T_{1S} or T_{1AC}				Risk reduction with individual measures			Risk and risk reduction with all T_{1E}, T_{1S}, T_{1AC}	
Commune	T_0	T_0	T_{1E}	T_0	T1	T_0	T_0	T_1	T_0	T_{1S}	T_0	T_{1AC}	T_0	T_{1E}	T_{1S}	T_{1AC}	Exposure reduced	Sensitivity reduced	AC increased	Risk	Risk reduction
Puerto Varas	**5.0**	**1**		2		5	4		**3.67**		**0.0**		0.15								
Cochamo	**5.0**	**5**	**4**	5	4	5	4	2	**4.67**	**4**	**0.0**	**0.2**	0.93	0.75	0.73	0.75	0.19	0.20	0.19	0.59	0.35
Puerto Montt	**5.0**	**4**		3		4	4		**3.67**		**0.0**		0.59								
Calbuco	**5.0**	**1**		1		3	3		**2.33**		**0.0**		0.09								
Ancud	**5.0**	**1**		1		3	3		**2.33**		**0.0**		0.09								
Quemchi	**5.0**	**2**		1		2	3		**2.00**		**0.0**		0.16								
Hualaihue	**5.0**	**4**		3		4	4		**3.67**		**0.0**		0.59								
Dalcahue	**4.8**	**1**	**2**	1		2	3		**2.00**		**0.0**		0.08	0.15							
Castro	**4.8**	**2**		2		2	3		**2.33**		**0.0**		0.18								
Chonchi	**4.8**	**1**	**2**	1		2	3		**2.00**		**0.0**		0.08	0.15							
Puqueldón	**4.8**	**1**		1		2	3		**2.00**		**0.0**		0.08								
Quinchao	**4.8**	**1**		1		2	3		**2.00**		**0.0**		0.08								
Chaitén	**4.8**	**1**		1		2	3		**2.00**		**0.0**		0.08								
Quellón	**4.3**	**2**		2		2	3		**2.33**		**0.0**		0.16								

Note: Risk is R = E*Va*H, where Va = S*(1-AC). Current farming conditions it is considered as time = 0; and is represented by "T_0" and a condition at a later time in which we have modified components to reduce risks it is represented by "T_1"; risk reduction is estimated as the difference between risk at T_0 and T_1. The symbol T1E corresponds to a reduction of exposure at T_1; T_{1S} corresponds to a reduction of sensitivity at T_1; while T_{1AC} corresponds to an increase of adaptive capacity at T_1. Scores for hazard (H), exposure (E), sensitivity (S) (1 to 5) and adaptive capacity (AC) (0 to 1), are shown for each commune. Values are described considering current conditions (T_0) for all the communes, and at T_1 only for Cochamo, Dalcahue and Chonchi where we have modified components to reduce risks. A red colour scale provides a comparative visual assessment of estimated risks from highest (darker red) to lowest (light red to white).

TABLE 15
Semiquantitative estimation of effectiveness, costs, and cost-effectiveness (C/E) for adaptation measures proposed to reduce mussel seed production under climate change. Effectiveness scores result from the estimated risk reduction points (Table 14) when the measure is adopted

	Adaptation action	Effectiveness	Farmers costs (for individual farmers)	Farmers C/E	Government costs	Government C/E	Cost for other stakeholders within the mussel value chain	Average cost (score)	Overall C/E (Av Cost/Eff)
Reduce exposure	Reduce seed production in communes with higher risk	2	3	1.5	2	1	2	2.3	1.2
Reduce sensitivity	Establish mussel beds conservation programe	2	1	0.5	1	0.5		1.0	0.5
	Improved seed collection systems to reduce seed mortality by poor handling	3	1	0.3	1.0	0.3		1.0	0.3
Increase capacity of adaptation	Improving monitoring of mussel larvae and seed	1	1	1	1	1		1.0	1.0
	Moving seed production to hatcheries on land	2	3	1.5	3	1.5	2	2.7	1.3
				Maximum C/E = 3	Minimum C/E = 0.3				

Note: Costs and effectiveness are estimated as High (3), Medium (2) and Low (1). Effectiveness of the measures is considered as Low (equivalent to 1) when risk reduction points are <0.15 (see Table 4); Medium (2) = 0.16–0.50; and High (3) = >0.50. Cost-effectiveness (C/E) is calculated as c(a)/e(a), where c(a) is the cost indicator and e(a) is effectivity. Thus, the minimum value of the cost-effectiveness index is 0.33 (a combination of lowest cost and highest effectiveness, that is 1:3). Therefore, this is a comparatively best option (greenest color), while the maximum value of the cost-effectiveness index is 3 (combination of highest cost and lowest effectiveness, red color). In the present case the worst option is 1.5 (light orange color).

less pressure on the seed pool, which means that more seed will be available to return to the bottom and support and strengthen mussel populations.

Increasing adaptive capacity is possible by implementing better environmental monitoring systems for mussel larvae and seed beds.

As is shown in Table 14, by **implementing three adaptation actions together** – that is, reducing exposure and sensitivity, and increasing adaptive capacity– risk in Cochamó could be reduced from 0.93 to 0.59: a significant reduction.

a) Estimating the cost-effectiveness of adaptation measures for mussel seed production
In the case of **reducing exposure** by reducing mussel seed production in the Cochamó commune, which is partially compensated with increases in seed production in other communes (e.g. Dalcahue and Chonchi, Table 14), the main impact in terms of costs is on the incomes of the families that depend on mussel seed growing in Cochamó. This could have a major impact since, in the exercise, the estimated reduction is nearly 42 percent of annual production. Yet it is not obvious how important this impact might be, since they have other livelihoods besides mussel seed sales. Nevertheless, the income loss from mussel seed production in this commune could be an upper limit of the accepted social cost of this adaptation measure. Moreover, the measure involves increasing mussel seed collection in other communes, which could bring some social benefits in those locations. This would reduce the total social cost of the measure, although it would benefit some groups/communes and impose costs on others. Finally, to the extent that the total supply of seed diminishes (since the adaptation measure is not capable of stabilizing total production, this situation could also induce an increase in the average cost of mussel seed, which might also have some additional economic

effects along the mussel production chain in terms of increased price of the mussel seed, because of the greater seed scarcity provoked by the adaptation measure.

The adaptation measures that **reduce sensitivity,** such as the mussel bed conservation programme in Cochamó or the improvement in seed collection to reduce on-site seed losses before harvesting, are relatively low-cost. These measures need state intervention to organize seed collectors and finance the programmes, and the participation of the seed collectors themselves, but the resources required are likely limited. There is a manageable number of collectors engaged in specific territories, and there do not seem to be other activities that could be affected by these programmes. So, from a cost perspective, these measures are well worth evaluating.

One frequently mentioned option is to replace seed collection with on-land production in controlled hatcheries. This measure is considered here as an **adaptive capacity** option (it is similar to the use of RAS in salmon farming) (Table 14). This is indeed possible because Chilean mussel seeds can be produced in hatcheries since the technology is known and it has been proven (Molinet *et al.,* 2015). However, the initial investment and the costs of seeds could be much higher, and there would also be a significant loss of livelihoods that currently depend on seed collection. Additionally, it is not clear that seeds produced in a hatchery will have sufficient resistance to variability in environmental conditions (Molinet *et al*., 2021). Thus, this measure seems to be less cost-effective overall – and yet in time, as science and technology improve, it could become better rated, offsetting initial investment costs. It is, however, less clear how to deal with the social costs.

In Table 15 we present the cost-effectiveness estimations for farmers in Cochamó, as well as for government and for other stakeholders involved in the mussel seed value chain. We also show estimated cost-effectiveness (C-E) as described above for salmon. Even though this is an estimative exercise, it can still highlight the advantages of some measures. This is the case for 'improved seed collection systems' (Table 15), which by reducing losses and therefore reducing pressure on mussel beds could be effective while costing no more than better management measures (e.g. with appropriate extension) and some improvements to the longline systems (Table 15). The establishment of a 'mussel beds conservation programme' can also be a cost-effective measure.

iv. Steps 5 and 6 – Implementation of the strategy, monitoring and evaluation

Implementation of the described measures for this case study involving mostly small-scale farmers which are in fact small-scale fishermen that have moved to small-scale aquaculture, requires a much stronger and comprehensive government intervention (as compared to the more intensive large scale salmon farming). Implementation of measures require a stronger coordinating role in local institutions, to promote farmers joint actions, also requires a well-designed extension and capacity building program. Improved management of seed collection requires a better understanding of the efficiency of the collectors and the advantage of reducing larvae losses in the collectors. Environmental monitoring and assessment of mussel larvae availability must take into consideration not only climatic variability and trends but also the fishing pressure of seed collector which can reduce the resiliency of parental mussel beds. Although some of these activities are already taking place promoted by the fisheries and aquaculture institutions a better coordination and support is needed. Also, a long-term monitoring of the effect of some measures should be implemented.

IV. MAIN TAKE-HOME MESSAGES FROM BOTH CASE STUDIES

- Aqua-Adapt presented in the two case studies here can help to evaluate alternative adaptation actions and support the selection of interventions as part of an informed policy process.

- Aqua-Adapt offers flexibility in terms of the type, amount and quality of data required. It could work in a poor data context as well as in a rich data context. It could also help to identify the type of data and information needed, which could be developed over time.

This framework may also be useful for the assessment of the effect of these measures in terms of risk reduction, reduction in exposure and sensitivity, increase in adaptive capacity, and increase in resilience over time.

- This framework requires that policymakers promote the collection of information about the cost and effectiveness of proposed measures from a range of stakeholders so they can take better-informed decisions.
- As the case studies presented here illustrate, different adaptation actions may have different levels of effectiveness depending on specific circumstances. These actions may also involve different costs, and the costs for a given action may vary across different stakeholders. The analysis may help to shed light on all these aspects and support informed policy decisions.
- The analysis presented here can be extended in different ways. For example, richer data may allow the cost of different actions to be estimated more accurately. The analysis can also be implemented at different spatial scales.
- Finally, Aqua-Adapt requires the monitoring of actions and measures and a periodic assessment/estimation of risks. Attention must also be paid to field assessments when adaptation units have experienced a hazard but have better adaptation measures in place and losses are reduced (and therefore risk in the face of future events is also reduced).
- A better governance for the design and implementation of measures is essential to: inform stakeholders, coordinate their actions, facilitate some actions and measures (e.g. policies and norms that are more flexible to changes in spatial location of farms)

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Annex 1

Summarized steps for applying the Aqua-Adapt. (Printable version)

THE STEPWISE PROCESS FOR APPLYING AQUA-ADAPT IS AS FOLLOWS

	To do	How	By whom
	**Step 1: Define the aquaculture adaptation unit** The framework's first step is to establish the unit of adaptation. This involves the farmed species and associated socioecological systems at appropriate spatial scales. The unit can be defined by: • Aquaculture geographical area (national, community or aquaculture zone, neighbourhood, etc.) • Aquaculture sector (e.g. catfish farming, tilapia farming, mussel farming, etc.) • Aquaculture-specific species (e.g. Atlantic salmon) • Other spatial, productive or geopolitical units • Production system (ponds, cages, tanks)		
	**Step 2: Evaluate and consider climatic projections and pathways** Select and define the climate change scenarios and the climatic projections and threats considered for the unit of adaptation. According to IPCC (2021[1], 2022[2]), these scenarios, known as Representative Concentration Pathways (RCPs) or Shared Socioeconomic Pathways (SSPs) in more recent models, consider various factors like economic growth, population changes, energy production, and land-use changes. They provide a framework for understanding how different policy and lifestyle choices can impact the climate. General scenarios, climate pathways and their impacts are available for large regions and ecosystems globally and it is possible to identify general hazards to fit into the risks assessments (Step 3). If available, use appropriate regional climate models. This could help to select the temporal scale – 10-year, 50-year, 100-year, etc. that will be used in the next step (risk assessment) • Select appropriate regional climate model • Select the temporal scale – 10-year, 50-year, 100-year, etc. • Select scenario (RCPs or SSPs)		

THE STEPWISE PROCESS FOR APPLYING AQUA-ADAPT IS AS FOLLOWS (CONTINUED)

	To do	How	By whom
	**Step 3: Perform or assess a risk and/or vulnerability assessment on the defined aquaculture adaptation unit** by establishing climatic projection pathways. These require the use of the best available knowledge and appropriate climatic projection models. **It is necessary to identify and predict** the most important hazards to guide adaptation and the timing of actions. <u>Evaluate predictions</u>: • Select an appropriate climate model • Define the temporal scale (10, 20, 50 years) • Select the scenario model (RCPs and SSPs) Understanding current trends and forecasts for the next few years, decades, and even to the end of the century is of paramount importance for the aquaculture sector's response to climate change. However, it is very difficult for the farmers themselves (especially small-scale farmers) to project long-term trends and changes, so governments should ensure they have a clear long-term vision of the risks the sector faces. <u>Perform a risk assessment to identify</u>: • **The main hazards,** and establish a chain of events/impacts on a defined temporal scale to prioritize addressing them. • **The exposure,** and assess the production, assets, and livelihoods that could be lost. • **The sensitivity,** and assess the factors that make the system more susceptible to climate change impacts (these could be internal or external to the aquaculture system) • **The adaptive capacity,** identifying or developing technologies and improving management to make the system more resilient. A risk assessment for a specific unit could consider individual risks for each hazard identified, or a combined risk comprising several (often related) hazards. During this process, it is essential that researchers, monitoring institutions, governments and other relevant stakeholders work in collaboration with farmers.		
	**Step 4: Design an adaptation work plan** Elaborate a work plan by considering options to reduce the identified exposure and sensitivity and to increase the adaptive capacity of the unit of adaptation. Identify the best adaptation options (taking into account their cost-effectiveness), and define actions for the relevant stakeholders and actors. A timescale for implementation should be agreed, including short-term, mid-term and long-term actions. Human and financial resources to implement the strategy should be put in place. The adaptation work plan should consider: • a timescale for implementation; • how to select the most appropriate adaptation actions and how best to implement them; • whether adaptation measures should be carried out by the government, farmers, scientific community, or through public-private cooperation; and • the cost and likely effectiveness of each action in reducing risk. Table A and Table B presents some examples of actions that can be taken to reduce exposure to risk: it can be used as a template for applying the Aqua-adapt.		

THE STEPWISE PROCESS FOR APPLYING AQUA-ADAPT IS AS FOLLOWS (CONTINUED)

	To do	How	By whom
	**Step 5: Implement the strategy following the work plan** The proposed actions of the adaptation strategy should be implemented. It is necessary that different stakeholders involved take on corresponding roles and sufficient human and economic resources are allocated. Implementing the strategy should be a transparent and participatory process with clear and realistic timelines and estimates of human resources and budgets required for the different activities. It may require technical support and training considering economic, technical, social and environmental aspects.		
	**Step 6: Assess implementation of the strategy by monitoring the implementation of the working plan** The actions and measures within the strategy should be monitored and evaluated to improve implementation, using timelines and indicators agreed by stakeholders involved in the development of the strategy. It is necessary to design monitoring indicators, e.g. loss reduction, and perform a cost-benefit analysis. The strategy's theoretical success can be assessed in terms of reduced risk. However, its true effectiveness can only be assessed by the extent to which it reduces losses when it is faced with a real hazard. Risk assessments can be repeated when the strategy has been partly or completely implemented.		

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SPREADSHEET TO ASSESS SHORT-, MID- AND LON-TERM IMPLEMENTATION ACTIONS

Tables A1 and Table A2 below serve as a template for the application of Aqua-Adapt step 4, guiding the development of the work plan. Tables consider the implementation of several different short- to mid-term and long-term adaptation measures and actions (short-term refers to actions taking place immediately or very soon). Examples of how to fill in the spreadsheet can be found in Table 5A and Table 5B in Chapter 2.

Short-term actions are normally non-regret or low-regret actions that would improve performance and resilience even in the absence of climate change; such actions could be implemented in a time span from one to five years, although this can be variable. Long-term actions take longer to be implemented and normally involve higher costs and greater input from governments.

TABLE A
Work plan spreadsheet to assess short- to mid-term (1 to 5 years) adaptation actions and measures to reduce risks (reduce exposure, reduce sensitivity, increase adaptive capacity) in response to the hazards identified (assessed in Step 3)

Adaptation options	Short- to mid-term actions					
	Actions	By government	By farmers	Public-private cooperation (P-P)	Cost implications	Risk reduction effectiveness
Reduce exposure						
Reduce sensitivity						
Increase adaptive capacity						

TABLE B
Work plan spreadsheet to assess long-term (6-10 years or more) adaptation actions and measures to reduce risks (reduce exposure, reduce sensitivity, increase adaptive capacity) in response to the hazards identified (assessed in Step 3)

Adaptation options	Long-term actions					
	Actions	By government	By farmers	Public-private cooperation (P-P)	Cost implications	Risk reduction effectiveness
Reduce exposure						
Reduce sensitivity						
Increase adaptive capacity						

This publication explores a tool to support the development of strategies for the adaptation of aquaculture to climate change. The six steps in Aqua-Adapt offer guidance on the establishment of the unit of adaptation, assessment of the main risks faced by it, how to select better adaptation options, plan the implementation of the strategy, and how to monitor its performance. Aqua-adapt guides and enable stakeholders to comprehend the different scenarios and actions necessary to adapt aquaculture to climate change using global literature and also a couple of case studies.

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