Climate-change Adaptation in the Aquaculture Sector

Guidance document (*draft*)

Produced under the EU Aquaculture Assistance Mechanism which is part of a Service Contract jointly managed by DG MARE and the European Climate, Infrastructure and Environment Executive Agency (CINEA).

December 2023

EUROPEAN COMMISSION

European Climate, Infrastructure and Environment Executive Agency
Unit D.3.1 — Sustainable Blue Economy

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Guidance document

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Luxembourg: Publications Office of the European Union, 2021

PDF	ISBN	doi:	-

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LIST OF ABBREVIATIONS

Term	Description
AAC	Aquaculture Advisory Council
AAM	Aquaculture Assistance Mechanism
AI	Artificial Intelligence
AUV	Autonomous Underwater Vehicle
AZA	Allocated Zone for Aquaculture
CAP	Climate Adaptation Plan
CC	Climate Change
CEN	European Committee for Standardization
CINEA	European Climate, Infrastructure and Environment Executive Agency
CMS	Cardiomyopathic syndrome
DG MARE	Directorate-General for Maritime Affairs and Fisheries of the European Commission
EAS	European Aquaculture Society
EATIP	European Aquaculture Technology and Innovation Platform
EEA	European Environment Agency
EFFAB	The European Forum of Farm Animal Breeders
EMFAF	European Maritime, Fisheries and Aquaculture and Fund
EO	Earth Observation
EU	European Union
FAMENET	Fisheries and Aquaculture Monitoring, Evaluation and Local Support Network
FAO	Food and Agriculture Organisation of the United Nations
FCR	Food Conversion Ratio
FEAP	Federation of European Aquaculture Producers
FHF	Norwegian fisheries and aquaculture industry research funding
FLAGS	Fisheries Local Action Groups
HAB	Harmful Algal Blooms
GFCM	General Fisheries Commission for the Mediterranean
GHG	Greenhouse Gas
IMTA	Integrated Multi-trophic Aquaculture
IPCC	Intergovernmental Panel on Climate Change
IOT	Internet of Things
LAWA	German Working Group of the Federal States on Water Issues
LPAS	Live Plankton Analysis System
MNSPA	Multi-annual National Strategic Plan for Aquaculture
MS	Member State
MCCIP	Marine Climate Change Impacts Partnership
NE	Northeast
OA	Ocean Acidification
OT	Outcome Target
PKD	Proliferative Kidney Disease
RAS	Recirculating Aquaculture Systems
RBT	Rainbow Trout
SAIC	Scottish Aquaculture Innovation Centre
SGR	Specific Growth Rate
SME	Small and Medium-Size Enterprise
UNE	Spanish Standardization Association

GLOSSARY

This glossary provides a short definition of the terms used in this document. It is taken from various sources, including the CEN Workshop Agreement and the Intergovernmental Panel on Climate Change (IPCC) 2022 Report (Annex II).

Term	Definition
Adaptive capacity	Ability of production systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.
Adaptation measures	Strategies and/or measures available and appropriate to address adaptation needs.
Adaptation needs	The circumstances requiring action to cope with the climate change effects.
Climate adaptation	Process of adjustment to actual or expected climate change and its effects. In this document, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities.
Climate Adaptation Plan (CAP)	Long-term strategic plan developed for a fishery, fish farm or national aquaculture industry to develop adaptation measures for climate change effects.
EFABAR	It is a voluntary code of good practices in support of responsible farm animal breeding developed in the EU-project Code-EFABAR.
Indicator	Quantitative, qualitative, or binary variable that can be measured or described, in response to a defined criterion.
Likelihood	Chance of a specific outcome occurring.
Opportunity	Possibility to obtain positive outcomes (consequences) from the occurrence of a climate-driven likely event. For example, increase of biomass and production capacity.
Outcome Target (OT)	Specific and measurable performance goals which is defined for an adaptation measure, based on the broad future objective.
Risk	Potential adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of this guidance documents, risks can arise from potential impacts of climate change as well as from human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and wellbeing, economic, social, and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.
Risks - Short term	In this document, risks that might occur "within a few years".
Risks - Long term	In this document, risks that might occur by 2040 or beyond.
Stakeholder	Individuals and/or groups of individuals with an interest or claim (whether stated or implied) which has the potential of being impacted by or having an impact on a given project and its objectives.
Vulnerability	Propensity or predisposition to be adversely affected. Note: Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harms as well as lack of capacity to cope and adapt to them.

1. INTRODUCTION

Background

EU food production systems, including aquaculture, are being challenged by climate changes resulting from global warming. This affects all forms of aquaculture, in inland and coastal regions. Short-term impacts, such as extreme weather events, can destroy production infrastructure and limit the amount of water available to cultured species. Diseases, parasites, predators, and algal or jellyfish blooms can also decrease production. Longer-term impacts associated with changes in water temperature, salinity, ocean acidification, oxygen content and (for coastal areas) sea level will have varying effects on aquaculture production that may require the diversification of cultured species, the relocation of sites or the allocation of new sites for production.

These changes may also provide opportunities to diversify to new species production or obtain faster growth of existing ones. On-farm adaptation technologies to variable or extreme conditions may be employed, and solutions provided by selective breeding, nutrition, welfare monitoring and biosecurity measures will help to increase the resilience of farmed species to these changes.

The European Commission's 'Strategic guidelines for a more sustainable and competitive EU aquaculture'[1] identify the need to adapt to and mitigate the effects of climate change to build resilience and competitiveness for the aquaculture sector. Member States (MS) are encouraged to support the development of sector-specific national, regional, transnational, or sea-basin Climate Adaptation Plans (CAP), consistent with national adaptation strategies and plans, as well as the corresponding European Committee for Standardization (CEN) standard for development of CAPs. Also, the European Commission's Guidelines on Member States' adaptation strategies and plans [2] could be a reference.

The 2021 EU Climate Adaptation Strategy[3] sets out how the European Union (EU) can adapt to the unavoidable impacts of climate change and become climate resilient by 2050. This Strategy aims to achieve smarter, swifter and more systemic adaptation as well to step up international action on climate change adaptation. Additional frameworks, such as the Water Framework Directive[4], Marine Strategy Framework Directive[5], Integrated Maritime Policy[6] and Sustainable Blue Economy[7], also consider climate adaptation and its direct link with sustainable aquaculture development.

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[1] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:236:FIN

[2] Guidelines on Member States' adaptation strategies and plans (2023/C 264/01). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52023XC0727(01)

[3] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change. COM/2021/82 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN

[4] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32000L0060&qid=1688470961126

[5] Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0056

[6] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - An Integrated Maritime Policy for the European Union. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52007DC0575&qid=1688472136403

[7] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on a new approach for a sustainable blue economy in the EU

In the international context, the Food and Agriculture Organisation (FAO) Strategy on Climate Change 2022-2031[8] builds on its 2017 strategy and contributes to the implementation of the FAO Strategic Framework 2022–31, reflecting FAO's vision of a world free from hunger and malnutrition where food and agriculture (including fisheries and aquaculture) contribute to improving the living standards of all, especially the poorest, in an economically, socially, and environmentally sustainable manner.

EU-funded projects (for example AquaVitae, CERES, CLIMEFISH, DOGMATiCC, FutureEUAqua, GAIN, iFishIENCi, PerformFish, SOCLIMPACT, among others) have contributed to strengthening the knowledge base for the design of impactful climate-adaptation measures in different sectors, including aquaculture. Many of the outcomes of these projects and other useful information are publicly available on the web platform Climate-ADAPT [9], which is a "one-stop shop" for climate adaptation established jointly by the Commission and the European Environment Agency (EEA) (see Annex II).

Specific objectives

This Guidance Document - developed with the EU Aquaculture Assistance mechanism (AAM – see Annex I) - **has the principal objective to support MS and the industry in creating and updating Climate Adaptation Plans for aquaculture**.

To do so, it identifies climate-change impacts, possible adaptation measures and good practices that can be applied by MS and by the industry to make the European aquaculture sector more resilient to climate-related changes.

Content of the document

The document is organised in the following sections:

1. An introduction and presentation of the objectives of the Guidance Document (this section).
2. A description of the methodology used to prepare the document.
3. An overview of climate change effects on marine and inland aquaculture production systems, representing the key technologies and species produced in the EU.
4. A step-by-step approach to create a Climate Adaptation Plan (CAP), through the provision of recommendations and examples of good practices for Member States (MS).
5. Examples of good practices in adaptation measures that could be implemented by MS authorities and the aquaculture industry. Also, a specific factsheet is dedicated to the opportunities offered by climate change.
6. Knowledge gaps and research priorities that can fill or better understand current and emerging issues and recommended policy actions that may facilitate its climate adaptation.
7. Concluding comments and recommendations.
8. Annexes containing further information on the EU Aquaculture Assistance Mechanism (Annex I), EU Climate-ADAPT portal (Annex II), aquaculture measures included in MS Multi-annual National Strategic Plans for Aquaculture

Transforming the EU's Blue Economy for a Sustainable Future. COM/2021/240 final. Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:240:FIN

[8] FAO Strategy on Climate Change 2022–2031: https://www.fao.org/3/cc2274en/cc2274en.pdf

[9] https://climate-adapt.eea.europa.eu/

(Annex III) and examples on Risks/Opportunities matrices from H2020 CLIMEFISH project (Annex IV).

It should be noted that this document does not include examples of good practices in climate mitigation (reduction of emission of greenhouse gases).

Climate adaptation has numerous cross cutting and horizontal elements that include environmental management, husbandry and welfare-related practices and regulatory issues such as access to space and water. The reader is therefore encouraged to also consult the Guidance Documents on … addressing these issues.

2. METHODOLOGY

Relevant and recent information on the effects of climate change on EU and global aquaculture was obtained from desk research and scientific literature review. In particular, numerous guidelines and handbooks from the Food and Agriculture Organisation of the United Nations (FAO), scientific publications, case studies and EU-funded project deliverables were consulted. The positions of European producer associations (for instance, the Federation of European Aquaculture Producers, FEAP) and the specific recommendations on climate risks published by the Aquaculture Advisory Council (AAC) were also considered. Additional information was derived from aquaculture good practices (for example, Best Aquaculture Practices (BAP), GlobalGAP and the Global Seafood Alliance) and standards documents (for example, related to equipment).

Further general information was gathered from the European Climate Adaptation Platform (Climate-ADAPT) - an online resource platform created by the European Commission and the European Environment Agency (EEA) to support adaptation to climate change. It provides a wide range of materials on a) the current and future vulnerability of regions and sectors; b) national and transnational adaptation strategies; c) adaptation case studies and potential adaptation options; and d) tools that support adaptation planning (*see Annex II*).

Information was also derived from the outcomes of EU research projects**,** including the EU Horizon 2020 (H2020) projects CERES (Climate change and European Aquatic Resources) and CLIMEFISH (Co-creating a decision support framework to ensure sustainable fish production in Europe under climate change) as the two most comprehensive sources. The information was also complemented by climate-related deliverables and reports from more recent and ongoing EU projects (e.g. FutureEUAqua, AquaVitae, DOGMATiCC, GAIN, iFishIENCi, PerformFish, SOCLIMPACT, amongst others).

The effects of climate change are in many cases happening faster than our knowledge development and hence some project outputs based on scenarios and models that are several years old may not necessarily reflect the current situation faced by the sector. Efforts have therefore been made to address this in the document.

The European Committee for Standardization (CEN) Workshop Agreement (CWA 17518:2020) is a consensus-built, repeatable methodology to develop a CAP and was the principal source for Section 4. The document is presented as a draft standard and there is no obligation to use it at national level, but it can contribute to the development of National Adaptation Plans and related processes. It may also be used as the basis for a high-level standard, such as ISO. Other key sources include the CLIMEFISH Deliverables 4.3 and 6.2 and related scientific publications, e.g. by Pham et al (2021).

Additional data was collected through two surveys launched in April 2023. The first targeted EU Member States and sought to understand the status of Aquaculture-specific Climate Adaptation Plans (CAPs) and/or the inclusion of specific measures for aquaculture in MNSPAs or National (Climate) Adaptation Plans to make the aquaculture sector more resilient to climate-related changes. The second was targeted at aquaculture industry associations and individual entities and focussed on the identification of good practices by the industry on the assessment of risks and opportunities and the development of adaptation measures. A total of 13 EU Member States and 12 industry stakeholders contributed to the respective surveys.

After collecting and analysing the information gathered through the different data collection activities mentioned above, good practices were identified and compiled aiming to cover the diversity of the European aquaculture.

Several rounds of consultations with climate experts have also taken place at different stages in the preparation of this document. In the preliminary drafting stage, two scientific experts provided recommendations on the document's structure and key climate issues and potential adaptation measures to be addressed. Once the draft was finalised, a second and broader round of consultation was held with additional scientific experts with the aim to refine the document's content, expand the information on examples of good practices and fill gaps and open points. In addition, the draft document served as a basis for an EU workshop held just prior to the Member States Technical Seminar in the context of the EU Special Event on Aquaculture held in Brussels in October 2023.

3. OVERVIEW OF CLIMATE CHANGE EFFECTS

This section presents the main climate change effects for aquaculture producers in terms of short- and long-term impacts (noted in italics) and risks in both land-based and marine production systems. The section is therefore divided into the main types of production system.

But climate effects are also related to geographical area. Reports (including those by the IPCC and EEA, but not specifically referenced here) show areas and sea basins in Europe that are more susceptible to certain types of climate effects – so called hotspots. It is therefore important to note that climate stressors and climate effects vary considerably across regions (of Europe), but also between regions and even local areas within a particular country.

3.1 Land-based production systems

For simplification purposes, land-based production systems are split in this document into pond systems and wetlands, lagoons, flow-through/raceways and Recirculating Aquaculture Systems (RAS).

3.1.1. Pond systems and wetlands

Fishponds are man-made constructions that maintain significant (more than 300 000 ha) artificial wetland habitats in the drying landscape in Europe.

There are two main types of fishponds - barrage ponds are located mainly in hilly areas, with an average size of ca. 25 ha and using natural streams and small rivers as their water source, while paddy ponds are in lowland areas and are significantly larger (average size ca. 50 ha) and generally deeper with water supplied in medium/large artificial channels. Water scarcity (and also sudden flooding) is therefore more of a threat to the smaller barrage ponds.

When ponds are managed, a specific natural-like 'fishpond ecosystem' is created, which closely resembles natural wetland habitats. Although it is an artificial system, its nutrient cycling processes are identical to natural semi-static wetlands.

Pond aquaculture provides ecosystem services, and these are closely related to climate change adaptation. They include carbon sequestration, microclimate regulation (the ability of standing waters and their vegetation to influence temperature and humidity), water storage (the ability of the ponds to store the area's available or surplus water throughout the year) and excess water retention (Palásti *et al*., 2020), keeping free the reserve space required for eventual storage of excess waters.

Fishpond production is typically managed in polyculture, where the Common carp is produced in combination with other fish species (e.g. Silver carp, Grass carp, European catfish, Pikeperch and Pike, etc.) of the same age class. Pond production is an extensive (or semi-intensive) farming technology that uses natural food sources (mainly zooplankton) often complemented with cereals.

The impacts of climate change on water availability, its temperature, and oxygen level have potentially negative effects on fish production.

The CLIMEFISH case study on pond farming in Hungary identified the following risks:

- Increased mortality due to biotic stress, which was classified as *moderate in the short-term and major in the medium-term*.
- Gradual changes in other modelled biological and bio-physical parameters suggest that the underlying negative changes in water quality and disease patterns leading

to higher exposure of diseases will occur gradually, thus *short-term likelihood scores are lower than the ones for long-term.*

- Increased phytoplankton production. Although this climate change effect is likely to occur, there is no agreement between scientists and farmers whether and to what extent it is negative.

- Increased evaporation, considered as a *major risk for the medium- and long-term.* Model forecasts clearly support that increased water loss due to evaporation hydrological will occur in the coming decades, thus the likelihood of this negative effect is very high.

- Suboptimal and subcritical dissolved oxygen levels were assigned a score of *major* for all scenarios *and time periods*. There is extensive literature on the link between oxygen levels and temperature regulated phytoplankton biomass, supporting the increasing occurrence of oxygen deficit in ponds.

In addition, the producer organisations from Czechia and Hungary replying to the survey indicated that the greatest risks in the short-term (next few years) are severe weather events, availability of water, the increase of Food Conversion Ratio (FCR) and increased number of predators. In the *longer term* (2040 and beyond), extreme water events and water availability were also identified by these organisations as the highest risks. Emerging cyprinid viruses were selected as both *short- and long-term risks* for the aquaculture sector.

3.1.2. Lagoons

Coastal lagoons are associated with the extensive or semi-intensive culture of sea bass, sea bream, mullets, and other sparid fish. The best-known term for this production system is the Italian 'valliculture', in which man-made enclosures capture fish migrating with the natural lagoon currents of the Adriatic coast. Lagoon or coastal wetland production of fish and crustaceans is practiced in southern Spain and Portugal, as well as in Greece.

In many cases, lagoons are havens for migratory birds and other animals. The value of this high biodiversity - coupled with their status as buffer zones between the sea and the land - is recognised by the fact that most lagoon areas in Europe are Natura 2000 sites or are considered protected zones. Aquaculture production in these ecosystems is generally at low (stocking) density.

The biggest threats to these systems could be the *short-term risks* of sea level rise and the intensity of coastal storms. Coastal erosion caused by a combination of these two factors puts lagoon areas at risk. In addition, fish cultured in these ecosystems are also sensitive to rapid changes in temperature, salinity, and dissolved oxygen.

Marine Climate Change Impacts Partnership (MCCIP) published in 2018 provides an overview and management options for saline lagoons across the UK[10]. The biggest climate change threats to saline lagoons are relative sea-level rise, and changes in seasonal temperature, storminess, and rainfall patterns.

As these climate change impacts are expected to vary between geographic regions, so are the effects of climate change on saline lagoons across Europe. Some saline lagoons may therefore remain relatively unaffected by climate change impacts, while others may be lost completely.

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10 Last accessed on 04/07/2023 and available at: https://www.mccip.org.uk/sites/default/files/2021-07/mccip-saline-lagoons-report-card_second-run_v3.pdf

3.1.3. Flow-through/raceways

Flow-through and raceway systems take water from rivers or wells and are associated with the traditional culture of rainbow trout (RBT) in many European countries. Other species cultured in these systems are trout species, sturgeon, African catfish, and tilapia. These generally require large volumes of high-quality source water and are therefore at risk when there are changes in the volume and quality of the input water. During prolonged droughts, less water can be pumped through the systems and operators may even not have access to water due to drought restriction provisions. When floods occur, water quality degrades abruptly, so pumping is not possible.

When dissolved oxygen levels fall, increased aeration is required, especially for the different trout species cultured in these systems.

As the CERES case study (Deliverable 4.2) on RBT production underlined, most production units are managed by SMEs (and some micro-SMEs) and rely on rivers, boreholes, or springs to provide water of sufficient quality and quantity on a continuous basis to maintain their stocks. Moreover, financial analysis within this deliverable showed that many (small) farms operate on relatively small profit margins due to the high costs associated with feed and other cash costs. Impacts of climate change that directly affect profitability could therefore be very serious for these small-scale producers.

The CERES predictions for RBT production in Denmark, Germany, Turkey, and the UK for 2050 showed varying economic effects of climate change, based on the number of days of optimum growth per year and how this number might change in the future. Their analysis suggested that, on average across each country, the number of days when water temperatures are within the optimal growing range is greatest in the UK, followed by Denmark, then Germany, and with the fewest in Turkey. They also noted the strong link between temperature and disease, highlighting that Proliferative Kidney Disease (PKD), causing impacts above 15°C, could be problematic for future temperature scenarios in all their reference countries, but especially in Turkey.

Producer organisations and or associations participating to the survey from Belgium, Croatia, Estonia, Slovenia, and Spain, whose members operate these production systems, identified water temperature and availability as the highest short-term risks for flow-through/raceways. These risks are associated with decreased production volume (and value) and increased losses (mortality), higher FCR and number of predators. Emerging pathologies, plus a rise in existing ones, were selected as a high risk in the short term.

In the longer term, the key risks identified by these organisations were mainly water availability and a decrease in production volume.

3.1.4. Recirculating Aquaculture Systems (RAS)

RAS are water-efficient and highly productive systems. The definition of RAS includes the recycling and reuse of water after mechanical and biological filtration. Typical RAS systems are indoor and recirculate almost of the incoming water and act as an almost completely closed circuit. However, all systems that are improved to use less water and to treat used water, are effectively "recirculation" or "partial recirculation" systems.

Because of their 'closed system' nature, RAS systems are removed from adverse environmental impacts, such as eutrophication, escapes, and parasite transmission, among others.

The effects of climate change are therefore considered to be less impactful for RAS systems operating indoors as high levels of control can be applied.

3.2 Marine production systems

For the purposes of simplification, in this document, marine production systems are split into floating cage systems for finfish, and inter-tidal or suspended culture for shellfish (from the surface or off-bottom) and seaweeds.

3.2.1 Cage systems

Floating cage systems, in units of several cages moored together and anchored to the sea floor, are used to produce cold and warm water fish species. The cage units are supplied by air-blown automatic feeding systems, and boats are relied upon for service and operations.

Climate effects are numerous and present both risks and opportunities for producers. They not only produce changes in the water physico-chemistry, but also include storm events, sea level rise, changes in the impacts of Harmful Algal Blooms (HABs), parasites, predators, and diseases.

For example, the EU-funded iFfishIENCi project[11] (Deliverable 4.3) suggested that increasing winter sea temperatures (*in the short and long term*) may be beneficial for productivity of its reference species and locations (Atlantic salmon for Norway and European seabass, gilthead seabream and meagre for Greece), with better fish growth during the winter period. In contrast, increasing summer temperatures will become sub-optimal *in the long term*.

In the Mediterranean, higher summer surface temperatures will at some point (*in the long term*) exceed the benefit of warmer winter temperatures and become problematic for the production of sea bream and sea bass. Other stressors, including dissolved oxygen and salinity changes, will also have variable effects on productivity that could be limiting at that point in time.

iFfishIENCi concluded that European marine aquaculture is vulnerable to climate change, especially in the summer months where there is an increased chance of a combination of higher temperatures and lower oxygen concentrations, increasing the likelihood of stress and mortality. More optimal winter and less optimal summer conditions may affect stocking patterns and production cycles, and these could have market effects when available supply is not in phase with demand.

In their study of climate scenarios and potential effects on marine aquaculture in Greece, Stavrakidis-Zachou et al. (2021) were more alarming. Studying predictive models for biomass production and profitability under a production scenario for 200,000 individuals, at 800g market size, they simulated three extreme event scenarios, namely:

1. "Mild extreme events" (1% mortality for heatwaves and storms).
2. "Intense heatwaves" (5% and 1% mortality for heatwaves and storms, respectively).
3. "Intense storminess" (1% and 5% mortality for heatwaves and storms, respectively).

These simulations suggested that, under the considered scenarios, the time period (2030, 2050) and the location of the farm (inshore/offshore) are among the parameters with the highest impact on biomass production and, by extension, on profitability. Compared to the current situation, the effects on biomass and profitability will be small

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[11] H2020 iFishIENCi. Intelligent Fish feeding through Integration of Enabling technologies and Circular principles. https://ifishienci.eu/ Deliverable 4.3 iFishIENCi Report on Climate change scenarios and impacts on aquaculture. https://zenodo.org/records/6684627

in the mid-term (2030) but will double for *the long-term* (2050) projections. Initially, the production volume will show marginal losses in the order of 0–16% leading to moderate profit losses, ranging between 1-25%.

However, the authors suggested that by 2050 biomass production and profit will drastically deteriorate across all scenarios. Decrease in biomass will generally be in the range of 25–40%, resulting in devastating effects for farm profitability. These results are attributed to the increased frequency of extreme events *in the long-term*, and predominantly to heatwaves. They concluded that, while the other considered factors may provide partial compensation for this significant loss of biomass, they might not be enough to salvage production.

However, the simulations presented above assumed no technological advances for the industry or genetic improvement for the farmed species. Similarly, no assumptions were made for other adaptation measures, such as diversification to other species.

The CLIMEFISH case study (2020) in Greece identified many risks with variable potential impact on the sector. The first two further support the effects documented in the previous paragraphs. Greek stakeholders identified the following key risks:

- Inhibition of growth and increase of mortality. This was considered as major risk within the biological category for both climate scenarios and time periods. This impact relates to the decreases of oxygen solubility in water at higher temperatures and, in turn, this decreases oxygen in water. With insufficient oxygen, fish appetite reduces, as well as their growth and survival rate.

- Increase of feed prices and higher fluctuation of feed prices. From the production category, these were the higher scoring impacts, both considered to have negative impacts on the aquaculture activity in Greece.

- Increases in both HABs and fouling of the net cages. From the ecological and environmental category, these were the major risks.

- Increase presence of pathogens. This was the impact which received the highest risk rating and was considered as a severe negative impact from both stakeholders and scientists throughout climate scenarios and time periods.

- Other impacts were all considered as moderate, such as the suitability of farm sites, water quality deterioration, risk for anoxic conditions, increased size variability, infrastructure damages, increased use of antibiotics, and increase of escapees.

A more recent publication (Falconner *et al*., 2022) provides an insight into the real-world complexities. Atlantic salmon (*Salmo salar*) production in Norway was used as a case study to illustrate the need to consider impacts from multiple stressors across different production stages and the wider supply chain. Based on literature searches and industry news, a total of 45 impacts and 101 adaptation responses were identified. Almost all impacts were linked to multiple climate stressors, and many adaptation responses can be used for a range of impacts.

A comprehensive knowledge base, such as that presented in the publication, can be used by the aquaculture industry, researchers, and policymakers as a foundation for more targeted and detailed climate change impact analysis, risk assessments and adaptation planning. An Excel file[12] provided in annex to the publication can therefore serve as a template for other regions and other species.

Regarding the survey carried out to support the preparation of this guidance document, producer associations in Croatia, Malta and Spain identified severe weather events as being the highest risk in the short and long term, with increased losses (mortality, escapes) being linked to that. However, water temperature and husbandry effects (e.g. increased fouling, higher FCR) were not generally considered as major risks in the short term.

3.2.2 Inter-tidal and suspended systems

The majority of European shellfish production uses inter-tidal structures to keep the molluscs off-bottom with racks, trays, bags, and stakes. A smaller but increasing percentage of shellfish (mainly mussels) is produced in bags (socks) attached to longlines and marked on the surface by buoys.

Shellfish production accounts for more than 50% of aquaculture activity in Europe and there are many different and interlinked issues that have direct impact, including increasing pH and salinity and various abiotic and biotic factors.

As the significant mortality since 2008 caused by a genotype of the OsHV-1 virus showed, shellfish are vulnerable to climate changes that lead to the emergence of new pathogens. But shellfish appear to have some capacity to adapt to climate change, with tolerance and/or resilience to environmental stressors and genetic adaptation to their changing habitants (Byrne *et al.*, 2020).

The CLIMEFISH case study on mussel aquaculture in Galicia identified the following key risks for the sector:

- Harvesting closure: Closure of mussel cultivation areas because of toxic phytoplankton (HABs).
- Lack of mussel seed (spat): Not only by recent cyclical reduction in natural spatfall, but also by increased predation of settled spat.
- Loss of rafts: Infrastructure losses due to storm activity.
- Detachment of mussels: Also, from storm effects.

In reply to the survey, the shellfish producer organisation in Galicia (Spain) confirmed the risks stated above. They indicated that water temperature is the highest short-term risk, with harmful (algal) blooms being of medium risk – but with both leading to decreased production volume. In the case of mussel production in the longer term, the identified risks remained at high and medium levels respectively, with the important additional risk of major fluctuations in natural spat recruitment, on which the mussel industry generally relies.

Suspended systems are also used for the farming of macro-algae (seaweeds). Currently, there is not extensive information on the impacts of climate change effects on EU algal

[12] S1 Appendix. Norwegian salmon aquaculture knowledge base (XLSX) https://doi.org/10.1371/journal.pclm.0000017.s001

production, but is expected to be enhanced by the EU Algae Initiative and its EU4Algae platform[13].

A recent report (van Duinen et al., 2023) addressed the impacts of scaling up the production of marine algae in the EU. It assessed the biomass, and the protein yields that algae can provide; the costs and Greenhouse Gas (GHG) emissions of different algae production technologies; the potential total algae biomass production in Europe as well as the resulting carbon dioxide captured and the potential share of (today and future) animal and fish feed requirements that could be met by algae production. While this is not specifically focussed on the effects of climate on algal production, it does present knowledge on the role of algae in climate change adaptation and mitigation.

[13] https://maritime-forum.ec.europa.eu/en/frontpage/1727

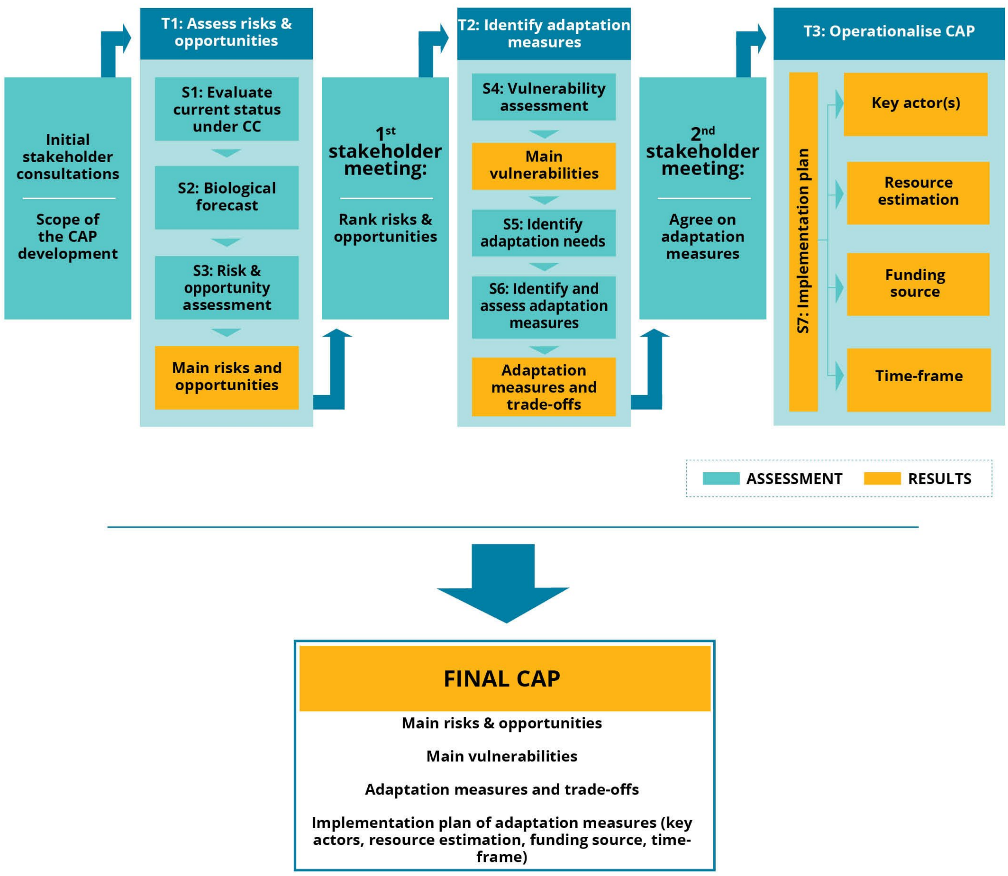
4. CREATING CLIMATE ADAPTATION PLANS FOR AQUACULTURE

This section has been designed to support Member States in developing a Climate Adaptation Plan for aquaculture. It is based on various information sources, but principally on a voluntary European standard to develop tailor-made CAPs, that has been published by the European Committee for Standardization (CEN) as a Workshop Agreement. Other key sources include the CLIMEFISH Deliverables 4.3 and 6.2 and a related scientific publication by Pham et al (2021).

The CEN Workshop Agreement (CWA 17518:2020) is a consensus-built, repeatable methodology to develop a CAP through a stepwise description on how to do it formulated as a standard. It requires open publicly announced meetings (at least two) and a hearing period, reinforcing participation and transparency. It is presented as a draft standard and may also be used as the basis for a high-level standard (e.g., ISO).

The CAP development process (Figure 1) results in the identification of realistic and efficient adaptation measures. It is split into three main tasks – T1: The assessment of risks and opportunities; T2: The identification of adaptation measures; and T3: The operationalisation of the CAP. For each task, the required stakeholder consultation/co-creation is indicated and the results/outcomes of each task and sub-task (S1-7) are shown in orange. It contains identified risks and opportunities; identified vulnerabilities; identified adaptation measures and an implementation plan.

Figure 1. CAP development process overview



Source: CEN Workshop Agreement. CWA 17518:2020

The CAP may be linked to the National (Climate) Adaptation Plan. This has the advantage of identifying the positive effects of aquaculture on resources that are potential benefits to other economic sectors. Examples include the reduction of eutrophication, flood buffering of pond aquaculture and the use of oyster beds to reduce coastal erosion and sequester CO_2. The CAP could also be developed to be linked or incorporated in the Multi-Annual National Strategic Plans for aquaculture. Finally, it could form the basis of a multi-stakeholder strategy and action plan.

The European Maritime, Fisheries and Aquaculture Fund (EMFAF) supports local partnerships to empower communities to maximise their environmental, cultural, social, and human resources and tap into the opportunities offered by the blue economy in their specific areas. Under a tool called 'community-led local development' (EC 2022) stakeholders from the community set up a 'local action group' to develop and implement a local strategy. It fosters small-scale collective initiatives and promotes innovations that help develop the local blue economy and protect the marine environment. This could therefore be used as an appropriate instrument - among others - to develop an aquaculture CAP.

4.1 Stakeholder participation

Stakeholder involvement is fundamental when developing a CAP. According to CEN Workshop Agreement, they must be involved in the process through open publicly announced meetings and allowing for a hearing period to go through the different steps and reinforce participation and transparency. An effective tool to make use of local groups is the Fisheries and Aquaculture Monitoring, Evaluation and Local Support Network (FAMENET, formally FARNET) and Fisheries Local Action Groups (FLAGS) under the EMFAF community-led local development.

The identification of relevant climate effects and good practices examples on adaptation measures come from the diversity within the stakeholder community involved. Several techniques can be used for stakeholder selection, but the aim is to ensure representation of the four pillars of sustainability by applying a stakeholder typology as shown in the following table (adjusted for the purposes of this Guidance Document).

Table 1. Stakeholder typology

STAKEHOLDER TYPE	STAKEHOLDERS
Producers: Those using space, placing infrastructure, or taking resources from the marine or inland production system. **Beneficiaries:** Those benefitting from the ecosystem services and goods created by the production system and delivered by the extractors. **Affected:** Those affected by the extractors and inputters, affected by the policy decisions, or impacted by the decisions.	**Primary operators (aquaculture producers):** Operators who provide the raw material for processing. In this case, aquaculture operators (producers) and/or aquaculture producer associations. **Secondary operators (processors):** Operators who receive the raw material e.g., processing companies and others who sell and/or market the products. **Related agencies:** Representatives of all main managers of resources/infrastructures that either affect or are affected by the production system in question, e.g., water managing authorities, environmental agencies, tourism, transport, and marine spatial planning.
Regulators: Those giving permission to occupy space or to extract/input materials, those with a controlling rule in the production system, 'hard' and 'soft' regulators.	**Sectoral authorities:** Representatives from the sector's key policy making bodies: the ministry in charge of the production system in question, directorates and directly related agencies.
Influencers: Those influencing policy.	**Scientists/expert groups:** Individual scientists and/or representatives from a

STAKEHOLDER TYPE	STAKEHOLDERS
	scientific institution or company with relevant expert knowledge. **NGOs, lobby groups, educators:** Individuals or representatives from groups that can influence and lobby, e.g., for policy, resource use, infrastructure.

Based on CEN Workshop Agreement. CWA 17518:2020

Once the stakeholders are selected, the CAP kick-off meeting can be convened to decide the role and level of involvement of stakeholders in the key steps of the CAP process. Funding arrangements should also be agreed to provide sufficient resources to develop the work. This can be enshrined in a CAP Agreement, signed by all stakeholders participating in the process as a commitment to the work to be done.

4.2 Risk and opportunity assessment methodology and process

The risk and opportunity assessment phase evaluates key climate-related impacts that are expected to affect the components of a production system. This therefore implies that the system should be broken down into its core components. Annex B of the CEN Workshop Agreement provides a potential template for this.

Impacts should be evaluated as resulting in risks or opportunities. As there are several different methods for assessing risks and opportunities, it is necessary to identify the most appropriate for each case, considering for example data availability and the nature of the production system. FAO's online EAF toolbox[14] provides an overview of different risk assessment methods, including selection criteria. Although it has been designed for fisheries, it is also applicable to aquaculture.

The assessment has three key steps:

1. **Scoping/background and biological forecasting** – based on data collection and prediction of climate models for a particular area/zone/region. This is usually done by an ecological/biological modeller.

2. **Identification of impacts** - detecting and describing the potential issues that climate change events can present for the aquaculture activity under evaluation. This is performed by all stakeholders.

3. **Risk and opportunity analysis and scoring process** – at this point, stakeholders agree on the severity of negative and positive effects on a 5-point scale (see Table 2). This is often achieved through measurement of the risk, and/or through actual experience of the primary operators. Major and transformative positive impacts should be enabled through the implementation of support measures (capacity building and financing) that allow for their rapid adoption.

[14] www.fao.org/fishery/eaf-net/toolbox

Table 2. Risks and opportunities assessment

Category /Risk Level of impact	Risk Description	Category/ Opportunity Level	Opportunity Description
No	Acceptable, not a risk.	No	Irrelevant, not an opportunity.
Minor	Acceptable; not specific control measure needed.	Minor	Limited opportunity, minor improvement to present conditions.
Moderate	Maximum acceptable level, management measure required in medium to long term.	Moderate	Potential opportunity for improvements, to be considered under special circumstances.
Major	Not desirable; Increase management actions or implement further risk control in the near future.	Major	Significant improvements to present conditions, actions should be considered in the near future.
Severe	Unacceptable; Major changes required to management in immediate future.	Transformative	Transformative opportunity to take immediate actions.

Once the risk or opportunity level has been agreed, all those with a rating of 'moderate' or above could be further assessed in order to have an overview of each component's vulnerability towards expected climate change impacts.

Adaptation measures can be built directly on the basis of this assessment.

4.3 Identification of adaptation measures

The aim of this phase is to define adaptation measures for each component of the production system under future climate change impacts. The objectives can then be further defined with indicators and outcome targets (OT). Some examples are presented in the table below.

Table 3. Examples of indicators and outcome targets for the identification of adaptation measures

Indicators	OT
Specific Growth Rate (SGR) and on-growing period at farm (time to market size)	Time to market size ≤ X days
Annual income (€ / year)	Increased Return on Assets (ROA) ≥ X € /year
Employment (as number of employees/farm)	Increased employment within industry ≥ X% of workforce
Number of days (annual) where husbandry operation procedures are inhibited due to limited infrastructure durability to extreme weather	Number of non-operational days ≤ X days

Indicators	OT
Feeding costs (€ / ton of fish produced)	Feeding costs ≤ X% of production cost

Once identified, the adaptation measures can be classified into categories of "ownership":

1. Industry level adaptation measures: Adaptation measures where operators are responsible for implementation and do not require changes in legislation. OTs and indicators are applied directly on the production process to evaluate success.

2. Policy recommendations: Adaptation measures targeted to the industry, but require prior legislative change or policy recommendations from local, regional, national, or European authorities in order to increase the resilience of the sector. Examples include more flexible legislation/limits, development of financial instruments to facilitate implementation of adaptation measures, or a facilitated insurance scheme. In this category, OTs and indicators are not required.

3. Research and knowledge gaps: These should be filled to allow implementation of adaptation measures or to help identify new measures or new emerging risks. No OTs and indicators are required for this category.

The EU Bioeconomy Monitoring System Indicator Update (EC JRC 2023[15]) contains proposed indicators for Climate Adaptation in Fisheries and Aquaculture. Specifically, indicators are proposed for reducing the trophic level of farmed animals, selective breeding for resilience, moving/planning siting of cage aquaculture, fish escapes, insurance schemes for SMEs; mollusc production persistence and fish production persistence. Common indicators include increasing resilience to climate related extreme events and reducing direct and indirect GHG emissions.

4.4 Implementation

It is very important that the stakeholders participating in all of the previous steps have some level of involvement in the implementation of the CAP. The level of details when describing the key actors in the CAP is up to the CAP consortium, i.e., whether it will contain specific names or designated groups (e.g., associations), or actors with specific professions and expertise (e.g., aquaculture producers, other local actors, policy makers, retailers, scientists, engineers).

In this phase, an estimation of the resources (at local/regional/national level) is desirable and could include labour costs, product development, infrastructure, technology, or other investment needed for implementation. The main sources of funding (e.g., private, stakeholder, research funds, EMFAF, etc.) should be documented.

In addition, the time frame expected for implementation of the CAP should be estimated in accordance with the required resources, mainly the time needed for both the planning and implementation of the adaptation measures until they are considered fully functional.

4.5 Monitoring and evaluation

Monitoring and evaluating the implementation of the adopted adaptation measures not only highlights the efficiency and progress of the measure, but also unexpected barriers that may require additional actions or improvements.

[15] https://data.europa.eu/doi/10.2760/19269

Monitoring indicators can also assist in the data collection and evaluation of climate change-related actions carried out by Member States.

Monitoring can be internal and/or external. Internal monitoring is generally performed by the operators or authorities and ensures that the CAP Plan is being adopted and implemented. External evaluation is generally carried out by an extended group of stakeholders and assesses the impact and success of the adaptation measures put in place.

4.6 Updating

Climate effects are happening now and may be relatively constant or rapidly accelerate in the short and medium term. However, the contributions to the existing knowledge on these effects and the development of technology to adapt to them takes time. Therefore CAPs must be periodically updated through a new round of consultations. For stand-alone multi-stakeholder strategies and action plans, the recommendation (from CLIMEFISH) is to update the CAP every three years.

The current approved MNSPAs are in place for the period 2021-2030. **In this context, the CAP preparation or update will have to take place before the next MNSPA cycle or National (Climate) Adaptation Plan.**

5. GOOD PRACTICES ON ADAPTATION MEASURES

This section provides examples of good practices that could help the aquaculture sector to adapt to climate change effects. The selected good practices are organised in six factsheets, which address a specific climate adaptation measure (see Table below*).* In addition, each factsheet presents background information on climate challenges as well as proposed solutions and measures.

The examples of adaptation measures and tools provided are in various stages of development and not all are commercially available for operators.

Table 4. Overview of good practices on climate adaptation measures

ADAPTATION MEASURE	GOOD PRACTICE	COUNTRY
Practical impact forecasting and decision-making tools	Artificial Intelligence (AI) to automate the process of identifying HAB. Weekly bulletin for farmers.	UK
	Automated data integration to existing systems to provide prediction measures for fish health & disease outbreaks.	Norway
	Provision of data on various environmental risks.	Italy
Selective Breeding for increased resilience	Key selection traits of current breeding programmes: examples of good practice in the management of breeding programmes and whether current strains are sufficiently tolerant to short term climate changes and/or disease threats.	Finland, France, Greece and Ireland
Production opportunities and diversification	Fast growing and/or new finfish marketed at a large size.	Europe
	Diversification of species.	Croatia, Malta
	New trout strains.	Germany
	Production of tilapia and shrimp.	Europe
	Turning toxic algae blooms into business opportunities.	Lithuania
	"Aquaculture Readiness Level" – for species diversification.	Norway
Infrastructure and system development	Technical screening criteria for escapes from sea cages.	UK
	Technical Standard for marine finfish cages and equipment.	Spain
	Underwater Vehicles for continuous automated net cleaning.	Norway
	System development in inland (pond) systems.	EU
	Annual risk analysis for specific farms and biosecurity analysis for farming locations.	Croatia
	Aquaculture Network to provide advice to SMEs on a case-by-case basis in the management of water use.	Germany

ADAPTATION MEASURE	GOOD PRACTICE	COUNTRY
Location planning and relocation	Using expert advice for relocation of farms/disease prevention plan.	Slovenia
	Urban farming: aquaponics systems to avoid climate effects and produce fresh locally available vegetables.	Czechia, Belgium and Germany
	A "suitability index" for site location in estuaries for shellfish production.	Portugal
Management of the introduction of non-native species	FAO technical guidelines, including good practices on quarantine measures and monitoring programmes.	EU

Aquaculture feeds (that make up a significant proportion of the environmental footprint of fed aquaculture species) are not addressed in detail in this document and good practices are not provided. While commercial feeds are available to help fish through the recognised "complicated stages" of the production cycle (maturation, larval weaning, overwintering, etc.), their continuing development could also provide a means (through nutrition) for climate adaptation.

But novel feed ingredients, sourcing and circularity issues are more closely related to climate mitigation and will therefore be covered in more detail in a future Guidance Document on that topic.

5.1 Practical impact forecasting and decision-making tools

Background/Challenges

Climate change effects can mean that the environment in which aquaculture production takes place is subject to increasingly rapid changes with potentially substantial impacts. These include storm and localised extreme weather events and blooms or swarms of algae, sea lice and jellyfish that can quickly create welfare problems for aquaculture stocks and/or food safety issues for shellfish production.

While mapping exists for harmful algal blooms – and regulatory monitoring is required in many countries not only for HABs, but also for sea lice – more precision of the algal species and their potential toxicity is now required. In addition, with surface water temperature/nutrient profiles changing quickly, warning levels need to be further developed. Algal and bacterial blooms (such as cyanobacteria) are also problematic in inland systems.

Jellyfish species have been considered as fouling organisms for some time in both cold and warmer waters. The recent occurrence of microscopic jellyfish in northern Europe - that is probably related to climate effects - is something new and has caused fish mortality from asphyxiation due to blocked gills.

It is therefore important that aquaculture operators have access to simple and reliable tools that can provide an early warning system for these events. The user interface of these tools (for instance, a web portal or phone app) is especially important for SMEs that may not have the resources (i.e. time or software) to access complicated forecasting programmes.

Proposed solutions/Adaptation measures

With efficient and easily accessible (i.e. mobile app or alert) warning systems, aquaculture operators can take measures to avoid mortality and/or, in the case of shellfish, to avoid potential food safety risks. These include drawing fish down from the surface (for example, by stopping feeding), harvesting fish early, moving them to another site, increasing aeration or deploying physical or bubble curtains around farms.

Concerning bubble curtains, aeration systems can be used to create an upwelling of cooler, oxygen rich water to the surface of the cage. Through the injection of small air bubbles, the density of the water at depth is lowered, which makes the water rise. When the water with the lower density hits the surface, it spreads out to the sides, pushing the surface water (and HABs) outwards. Bubble curtains can also be produced from aeration at the bottom cage ring, providing a potential barrier to "undesirable" organisms (sea lice, jellyfish) in the water column.

Also, there are several satellite-based tools available for detection and forecasting. Three examples are provided here.

Copernicus Marine Service[16] provides with Earth Observation (EO) datasets for climate monitoring and forecasting.

One Copernicus tool is **S-3 EUROHAB**[17] – Sentinel-3 satellite products for detecting Eutrophication and Harmful Algal Bloom events in the French-English Channel. S-3 EUROHAB has developed a web-based Harmful Algal Bloom and Water Quality alert system that uses satellite data to improve the ways in which these parameters / phenomena are monitored. The system was designed by scientists in collaboration with stakeholders, in particular marine managers, and shellfish end-users. The system is using data from the European satellite, Copernicus Sentinel 3, to track the biomass and spread of HABs.

The **Interreg Atlantic** project PRIMROSE[18] (Predicting the impact of regional scale events on the aquaculture sector) has produced a web portal with various indicators available, including HABs. It continued work started in the previous (FP7) ASIMUTH project, by improving the accuracy of forecasts (with a traffic light system), increasing the regional coverage (improved spatial resolution provided by new generation EO Sentinel satellite data) and increasing the number of controlled parameters.

[16] Copernicus Marine Service: https://www.copernicus.eu/en/copernicus-services/marine

[17] S-3 EUROHAB: https://s3eurohab.eu/

[18] PRIMROSE project – web portal: https://primrose.eofrom.space/

5.1 Practical impact forecasting and decision-making tools

The **EMFF SEASTAR** project[19] has tested underwater Internet of Things (IoT) monitoring systems that provide quantitative data to support studies on climate change, ecosystem services and fish welfare. A fully integrated node/gateway/cloud system provides real-time high-resolution data to detect and record rapid changes in physical variables (i.e. temperature, oxygen, salinity), but also to monitor fast occurring changes (i.e. thermal anomalies) that may be related to extreme weather events. The project has led to a pilot phase in the Gulf of Follonica (Tuscany, Italy) in collaboration with nine producers (8 fish and 1 shellfish). The reference area is an allocated zone for aquaculture (AZA) and will be nested with sensors. The sensor data will be validated with satellite data and with in situ data and will be made available to the producers.

Examples of good practice in EU Member States and other countries

Good practice in forecasting and decision support tools relates not only to the tools used themselves, but also to the way in which the data is presented, standardised, and shared (simple traffic light systems), the accuracy and extent of provisions (number of days forecast) and the recommendations for action provided by the reports.

In Scotland, the Scottish Aquaculture Innovation Centre (SAIC) is producing an early warning system for salmon farmers that uses AI to automate the process of identifying HABs. This Live Plankton Analysis System (LPAS[20]) provides real time data and digital image analysis to prevent threats to welfare and reduce mortality. In addition, the Scottish Association for Marine Science (SAMS) operates a web-based HAB early warning system for the Shetland Islands[21] where many salmon farms are located. The portal provides a searchable map of current and historic HAB conditions, a "flash" indicator on toxin alerts status and whether action is required as well as an option to download a weekly HAB assessment.

An AI-based computer system developed in Ireland identifies up to 12 species of phytoplankton known to cause distress in farmed salmon. The system (which in future iterations will involve automatic sampling at various depths) counts and identifies phytoplankton in a water sample before calculating numbers per ml. The system allows fish health practitioners to build a reliable database of phytoplankton occurrence and introduce suitable mitigation.

Several companies throughout Europe propose a package of solutions for real-time monitoring and forecasting of multiple parameters.

In Norway, an online platform with automated data integrations to existing systems provides a range of prediction measures, fish health impact (benchmarking) tools and disease outbreak alerts.

In Italy, integration of satellite data with in-situ water samples and mathematical models provides tools for the effective management of environmental risks that can impair fish farm productivity. Water quality changes, storm activity and early warning of HABs can be predicted and depending on location, users have a five- to seven-day window to implement contingency measures before a farming site may be compromised.

In Denmark, an IT tool is under development that will collect online environmental big data from mussel farms, translate them in user-friendly format and send them directly to monitoring authorities to accelerate and systematise the monitoring process.

In Poland, (Panicz *et al.,* 2022) forecasting tools have been developed to assess the risk associated with the impact of climate change on three key viruses, both in the short-term (through mid-century) and long-term (to the end of the century). Specifically, the tools are risk maps that consider the geographic regions, the impact of temperature on both the viruses and the diseases they cause, and the effect of temperature on carp growth – for example, the number of days with temperatures favourable to disease development. The information in the risk maps is combined into a suitability map so that farmers can assess how their farms and businesses will perform in relation to these pathogens as the climate changes.

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[19] EMFF SEASTAR project: https://www.seastar-project.eu/

[20] LPAS: https://www.sustainableaquaculture.com/projects/project-list/live-plankton-analysis-system-lpas/

[21] https://www.habreports.org/

5.2 Selective Breeding for increased resilience

Background/Challenges

While the techniques used for breeding programmes (notably genomic selection tools and practices) have dramatically improved in recent years, the traits that are selected for are often production (faster growth, better fillet yield) and (existing) disease resistance related. Several national programmes are also selecting fish for better assimilation of feeds with novel (non-fish meal/oil) ingredients.

However, specific climate resilience related to environmental effects and especially increased summer water temperatures is not generally present in current breeding programmes and in many cases, **the current strains are not considered sufficiently tolerant to climate related changes.** Industry respondents to the survey indicated the need to factor these into the current breeding programme management.

Most breeding programmes operating in Europe are linked to the European Forum of Farm Animal Breeders (EFFAB) and to its the code of good practices for selective breeding (Code EFABAR[22]) which is reviewed/updated every three years.

The information in the examples below was obtained from several experts in breeding. For each country and (dominant) species, summary information is provided on the key selection traits that the current breeding programmes are selecting for; examples of good practice in the management of this programme and whether in their opinion the current strains sufficiently tolerant to short term climate changes and/or disease threats. There is no good practice *per se* for breeding for resilience to climate-related changes.

Examples of the characteristics of breeding programmes in EU Member States

In Finland, rainbow trout are selected for growth, maturity age, body shape, survival, carcass, resistance against *Diplostomum* parasite and skeletal deformations.

Good practice in the management of this breeding programme includes:

- Selection in a balanced way for productivity, fish health and reduced environmental impact (FCR is improved, resulting in less nutrients to the environment).
- Pedigree of individuals is maintained, allowing to maintain genetic diversity and to control of inbreeding.
- People managing the programme are highly skilled.
- Biosecurity is controlled.

However, it is considered that the current strains are not sufficiently tolerant to short-term climate changes/disease threats. Indeed, water temperatures are often above the tolerance level of rainbow trout. This impacts negatively broodstock fish, eggs, fingerlings, and on-growing fish, i.e. all life stages. There are also diseases that are temperature dependent (e.g. *Flavobacterium columnare, Saprolegnia fungus*) that have drastic negative effect on the industry. Finally, there may be diseases that spread northwards due to increased temperatures.

In France, rainbow trout are selected to improve:

- Growth to portion size (300 g) or large size (2-3 kg). This provides genotypes that are more able to maintain production from autumn to spring as growth in the summer has to be decreased with the increase of water temperature.
- Carcass, fillet, and trimming yields. The improvements are providing genotypes with higher feed efficiency (see later) less demanding in oxygen in summer.
- Disease resistance (*F. psychrophilum*, IPN, VHS).
- Female reproductive performance.
- Farming practices (density; fish meal/oil substitution; repeated grading; acid or alkaline water composition.

Most of the trout used in production are monosex females. All-female populations are less prone to the fungal disease (Saprolegniasis,) during male early maturation occurring in bisexual populations.

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[22] Code EFABAR: https://www.effab.info/modern-animal-breeding/responsible-breeding/code-efabar/

5.2 Selective Breeding for increased resilience

Examples of good practice include:

- Management of genetic resources and conservation of genetic variability based on pedigree tracing by genomic tools. Sperm cryopreservation through the French aquaculture cryobank CRYOAQUA.
- Indirect selection to improve feed efficiency (and having fish less demanding in oxygen) since 12 generations in rainbow trout (gain of 20 % in 10 generations, Vandeputte et al. 2022) and in sea bass (gain of 19 % in 6 generations, Monteiro et al., 2023,).
- Marker assisted or genomic selection to improve disease resistance (see Boudry et al., 2021) to 8 diseases in sea bass, sea bream, rainbow trout and Pacific oyster in using the FORTIOR Genetics Platform[23] in partnership with the National Reference ANSES Laboratory.
- R&D to estimate genetic basis for selection against hypoxia (see Prchal et al., 2022) and hyperthermia (see Lagarde et al., 2023) and cardio-respiratory capacity on diploid and triploid rainbow trout.

The current lines need to be adapted to climate change. The effect of water temperature increase is expanding rapidly. Major needs identified are in the improvement of growth and survival in hyperthermia, and improvement of the cardio-respiratory efficiency in diploid and for the triploid final products.

In Ireland (salmon), the breeding programme is focused currently on cardiomyopathic syndrome (CMS), growth, late sexual maturity, and pigment. The weights on each of these traits differs between the nucleus and production broodstock programme.

Good practices include:

- Maintenance of inbreeding to < 1% per generation.
- Broad selection index in nucleus (compared to production broodstock).
- Strong focus on disease resistance.
- Commitment to responsible breeding through Code EFABAR[24].

Regarding the robustness for future climate effects, only one strain farmed in Ireland (Mowi Strain) is recognised as being fairly robust, but no strain is completely tolerant to disease or higher temperature effects. An additional constraint to future breeding programmes in Ireland is that there are no facilities for testing and challenging fish for disease or, e.g., temperature tolerance.

In Greece, sea bass and sea bream programmes are mainly focused on improving growth rate. Additional selected traits include "natural" shape and appearance. Several programmes operating in the Mediterranean also include disease challenge traits. Other traits that are at least monitored for changes due to selection are fat percentage and viscera percentage.

Good practices include:

- Maintenance of genetic diversity by genotyping and pedigree management. Testing of selection candidates under normal production circumstances (to keep fish adapted to the environment).
- Strong biosecurity of broodstock facilities.
- Breeding program descendants are kept in more than one location (to protect against loss of the population due to disaster).

The current strains are not sufficiently tolerant to short term climate changes/disease threats. The fish typically survive temperature highs, but do need management interventions, including reduced feeding and oxygen supplementation. Disease threats are present and tolerance to fluctuating environment (extreme events) is not clear, but mortality events do occur during disease or extreme weather events.

5.3 Production opportunities and diversification

Background/Challenges

[23] https://www6.inrae.fr/sysaaf_eng/Fields-of-expertise/FORTIOR-Genetics-Platform

[24] http://www.responsiblebreeding.eu/

5.3 Production opportunities and diversification

The opportunities for climate effects may be listed as follows:

- Improved winter growth.
- Reduction of the overall life cycle (egg to harvest) duration.
- Potential production of larger individuals at market size (example sea bass).
- Increased primary production for pond aquaculture.
- Increased algal production for faster shellfish growth.
- Production of existing species in new areas/zones.
- Production on new species in existing or new areas/zones.

The potential for farming in new locations, with new areas and sites being increasingly optimal for production or use currently AZAs for production of species that are more resilient or tolerant of climate effects in that zone could help expand overall (EU) aquaculture production.

Diversification towards new species is, however, not a straightforward issue. There are possibilities, but each candidate species should be studied and its "readiness for aquaculture" should be defined and all trade-offs considered.

Proposed solutions/Adaptation measures

The CLIMEFISH and CERES case studies showed opportunities for many farmed **based on increasing water temperature.** These are not adaptation measures *per se*, but highlight the potential benefits for operators producing the following species:

For carp farming in Hungary:

- Increased individual growth rates and yields.
- Improvement in stocking and harvesting strategies with extended growing season.
- Increase of phyto- and zoo-plankton production in ponds.

For salmon farming in the Northeast Atlantic:

- Regional and temporal changes in individual fish growth.
- Change in feed costs due to change in food conversion rates.

For seabass/sea bream farming in Greece:

- Increase of biomass and production capacity.
- Seasonal changes in growth and stocking timing.

For shellfish (mussel) farming in Spain:

- Faster growth, related to harvesting strategy and potentially availability of phytoplankton in the water column.

Additional examples of the Opportunities Grids are shown in Annex IV.

How risks and opportunities are perceived depends on the circumstances of individual sites, operators and supporting environments. Impacts do not usually occur in isolation and compound events and multiple stressors are the reality for farming.

Fish (or any other species) growth is influenced by many different factors. Models that only consider temperature on fish growth under relatively controlled conditions may not therefore be fully applicable to real production conditions.

Examples of good practice in EU Member States and other countries

The FP7 project DIVERSIFY[25] (developed from 2013 to 2018) assessed the culture potential of meagre (*Argyrosomus regius*) and greater amberjack (*Seriola dumerili*) for warm-water marine cage culture, wreckfish (*Polyprion americanus*) for warm and cool-water marine cage culture, Atlantic halibut (*Hippoglossus hippoglossus*) for marine cold-water culture, grey mullet (*Mugil*

[25] http://www.diversifyfish.eu/summary.html

cephalus) a euryhaline herbivore for pond/extensive culture, and pikeperch (*Sander lucioperca*) for intensive culture using recirculating systems. These new/emerging species are fast growing and/or large finfish species marketed at a large size and can be processed into a range of products to provide the consumer with both a greater diversity of fish species and new value-added products.

According to the responses to the AAM survey, producer associations in Croatia and Malta see diversification of species (and new farm locations) as an opportunity.

Producer organisations in "inland aquaculture" countries also identified new species as a potential to increase/diversify production. In its Deliverable 4.2, CERES cites the example of farming different species or strains of trout to overcome environmental changes, for example, the so-called "BORN"-strain of Rainbow trout produced in the northeast of Germany. In other parts of Germany, sturgeon has been produced in trout farms when the water is too warm for trout. But of course the species produced needs to comply with EU and National legislation and regulation.

While not a direct result of climate change effects, or as a specific adaptation measure, the production of warm-water species tilapia and shrimp is being developed, especially when combined with recirculating technology that can be temperature controlled. Although there is already a wide global market for tilapia, the recent emergence of disease within several key producing countries may mean that there are new market opportunities. However, the limiting factor of tilapia is that they are cold sensitive and will stop feeding if temperatures drop below 17°C. The Euroshrimp Forum[26] has been set up as a point of contact for European shrimp production in RAS systems and its stakeholders.

Led by the Nature Research Center in Lithuania, the EU-LIFE funded project AlgaeService[27] is looking into ways to turn toxic algae blooms into business opportunities. The project has developed two prototype algae and cyanobacteria harvesting machines and tested in rivers and lakes in Lithuania, Poland, and the Curonian Lagoon (a UNESCO Heritage Site). The collected material will be used to produce biogas, slow-release fertilisers, and other plant growth promotors. Ended in November 2023, the project will produce a business plan for macro-algae and cyanobacteria.

In Denmark, focus is being given to the combination culture of seaweed and shellfish species, where new seaweed species will dominate in local cultures, such as the combination of Gracilaria and Pacific oyster.

The concept of "Aquaculture Readiness Level" has been proposed in Norway to assess whether farming of a range of existing and potential species will be successful. The study considered about 50 different species of fish, algae, crustaceans, bivalves, etc. The aquaculture readiness level is determined by defining what is known of the biology, technology and (growth) potential in different areas and under varying (environmental and climate-related) conditions for each species to determine whether it can be successfully farmed in that area. It could therefore be a useful tool for assessment in other countries and regions.

[26] Euroshrimp Forum: https://www.euroshrimp.net/home/

[27] AlgaeService: https://algaeservice.gamtostyrimai.lt/

5.4 Infrastructure and system development

Background/Challenges

With increased risk of storms and their effects on European marine aquaculture infrastructures, several challenges have emerged. These include the need for strengthening equipment, improving the (husbandry) management of the site, and net cleaning/fouling removal. Many of the expected climate effects are of short duration and have short-term effects, such as more frequent and intense storms; while others are present now and will become considerably more significant, such as water temperature, water chemistry, fouling, etc.

For inland systems, the focus is on managing the water resource (i.e. using less water in flow-through systems and reducing evaporation losses in larger pond systems) and the use of new production systems within ponds that would minimise the negative effects of climate change. Reduction of the total water volume can be achieved with partial or full recirculation aquaculture systems (RAS).

In marine systems, new cage systems that are semi or fully contained create a "barrier" to environmental interactions and a buffer to climate effects.

Proposed solutions/Adaptation measures

New equipment standards

Development of stronger, more resilient equipment, using new materials and fibres, is an ongoing process, driven by research and developed by the equipment manufacturers. New technical standards are either initiated as self-regulation by producer organisations, or as government regulations.

In response to the AAM survey that accompanied the preparation of this document, several MS and Industry Organisations highlighted new equipment standards as one of their climate adaptation measures.

New technologies for net inspection and cleaning

Net inspection (for damage, holes, etc.) has generally be done by divers, either on a routine basis, or when damage has already been done. With increasing pressure on cage systems through extreme weather events, the aquaculture industry is now looking to Autonomous Underwater Vehicles (AUVs) or drones to routinely monitor the net integrity and identify weak zones before any damage is done.

Cleaning nets of biofouling organisms has always been a husbandry task. Clean nets ensure optimum flow of water through the cages and therefore improves fish welfare. For many years, research has focussed on the development of anti-fouling products, although none are routinely used at present. Instead, nets are manually cleaned, and this involves lifting a part of the net above water and cleaning manually with high pressure water, or with various equipment such as drum cleaners. As fouling is likely to increase with rising water temperature, new and more efficient solutions are required.

Increased monitoring of the production environment

Monitoring of the production environment is a routine husbandry activity that allows better and more efficient production. Various water parameters are measured either periodically or in real time. This should include both biotic and abiotic factors.

With predicted short-term climate effects, increased monitoring in the form of risk analysis for each production site is recommended. The risk analysis should ideally include environmental parameters, indicators of potential environmental stressors (such as reduced oxygen levels, reduced water currents, etc.), but also equipment inspection and testing (routinely and especially after storm events). The monitoring should be linked to action plans to remediate them. In addition, operators should be trained in the measurement and recording of parameters as well as in the implementation of action plans.

System development in inland (pond) systems

With increasing predicted variability in water volume and quality, inland producers face increasing challenges related to water use. Economies in the total volume used can be made with recycling and water losses due to evaporation can be reduced with shading. New system developments in pond aquaculture include the "cage in pond" combination of intensive and extensive production, and the "tank in pond" systems that can increase the survival of early

5.4 Infrastructure and system development

life stages that are most vulnerable to climate-induced effects and predation or culture other species under intensive conditions in the extensive pond system.

RAS systems

As mentioned in section 3, RAS are water-efficient and highly productive systems**,** generally removed from adverse environmental impacts, as they are "closed" systems.

Many of the bottlenecks to financially viable operations have or are being overcome and technologies to optimise production are being implemented. In its 2020 study, the European Market Observatory for Fisheries and Aquaculture Products (EUMOFA) reported that production of fish for human consumption in recirculation systems was relatively stable at 1,5 to 2% of the total aquaculture production in the EU between 2009 to 2018, with an average yearly volume of nearly 24.000 tonnes. RAS production is dominated by a few countries, namely Denmark, the Netherlands, France, Germany, Poland, and Spain, which together accounted for 92% of the production in 2018.

The move towards RAS is therefore seen as a "climate-proof" step and innovation is rapid to decrease its cost and increase its energy-efficiency. It is therefore expected that the percentage volume of EU production from RAS systems will significantly increase over the next decade.

(Offshore) marine closed and semi-closed containment systems are being developed and tested at industrial scale in several countries. In Norway, CtrlAQUA[28] significantly furthered knowledge and innovation for establishing closed-containment systems within strategic parts of the Atlantic salmon production cycle. These systems may strongly reduce challenges with lice, escapees, and fish losses, offering a controlled and safe production environment that is far less susceptible to climate change effects.

Several innovations are, however, needed to bring closed-containment systems to a level where predictable production of Atlantic salmon in these systems can become a reality. These include reliability and cost-efficiency compared to traditional cage culture and the improvement of fish robustness (physiological and health/welfare) in these systems.

Examples of good practice in EU Member States and other countries

New equipment standards

In 2015, the Scottish Government published a Technical Standard for Scottish Finfish Aquaculture[29] that covered all fish farming equipment and was principally designed to prevent fish escapes due to equipment failure. It was implemented under a regulation of the Aquaculture and Fisheries (Scotland) Act 2013, which allows Scottish Ministers to require Scotland's fish farming industry to adopt a Technical Standard and ensure a suitably trained workforce. All equipment was expected to meet the requirements by 2020 at the latest. Its Annexes provide guidance on site operating procedures and templates to deliver the objectives of the develop the standard.

In 2019, Spain developed a Technical Standard for marine finfish cages and equipment (particularly against storm damage). The standard was elaborated by UNE, the Spanish Standardization Association, under its Technical Committee 173 Aquaculture processes and products (Standard Name: UNE. Marine aquaculture, Marine fish farms: design and operation. UNE 173202[30]). During its development, similar standards were analysed, for example ISO 16488: Marine fish farms-Open net cage-Design and operation. It was financed by the Spanish Ministry for Agriculture, Fishing and Food. Its implementation is voluntary, but needs to be certified by a third party.

While not a new standard, a company based in Ireland is proposing a system of springs designed for use in long-term mooring applications such as cage aquaculture against extreme weather events. The spring absorbs shocks and buffers the stress on the mooring system. Different types of spring can be used to reduce load and fatigue and hence reduce the overall risk of breakage, net tearing and other damage caused by storms. By their action, the springs

[28] https://ctrlaqua.no/innovation/

[29] Available at: https://www.gov.scot/publications/technical-standard-scottish-finfish-aquaculture/

[30] UNE 173202:2019: https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0062824

absorb energy, and future development of the system seeks to harness the energy for other systems that are in use on the cages.

New technologies for net inspection and cleaning

Several technology companies in Norway are developing Automated Underwater Vehicles to keep nets clean and that run autonomously. One of these is using partial funding from the Norwegian fisheries and aquaculture industry research funding (FHF) to develop an automatic net inspection drone. After initial computer simulation studies, an existing prototype used for pelagic fisheries research was tested in salmon cages. While the performance of the prototype was the primary objective, it was also noted that the algorithms managed to filter out disturbances such as the fish swimming between the vehicle and the net and the fish were not affected by the presence and operation of the drone, calmly swimming near it.

Increased monitoring of the production environment

In Croatia, the biggest producer has developed risk analysis for specific farm location (updated each year), as well as Biosecurity Analysis for farming locations.

The risk analysis includes potential diseases related to the location, juvenile controls, predator controls, environmental parameter measurement and controls, fish feed controls, vaccination plans, farm inspection plans and proposed measures for possible mortalities or disease outbreak events. Operational protocols and new reporting tools have been developed and incorporated to implement this.

In Greece, the AQUASAFE monitoring tool and decision support system has been developed and tested. The integrated monitoring and decision support system used both satellite and *in-situ* data to monitor aquaculture facilities on various scales, providing information on water quality, fish growth, and warning signs to alert managers and producers of potential hazards. The assessment of parameters and establishment of indicators have been documented (Chatziantoniou et al, 2023) and the software is being provided to operators.

In Ireland, systems for blood testing of fish to identify welfare or disease early before the fish exhibit physical symptoms, enabling better management and intervention are commercially available. Blood samples are taken by the farm for rapid transportation to the laboratory. The samples are checked against a range of blood biomarkers. Data is interpreted using algorithm-based AI models and presented within 24h enabling data informed husbandry decision making. The process is quicker than traditional histology methods and helps to create an overall view of the health of a fish population allowing rapid and insightful management decisions at farm level.

In France, in the Étang de Thau (a coastal lagoon on the Mediterranean), higher temperatures encourage algae growth, which decreases the available oxygen with negative impact on oyster production. In a joint project with companies, producers are using sensors to identify areas with low oxygen and employ oxygen injection. And on the west coast, to prevent microalgal blooms in the 'clairs' (saline pond systems where oysters are held for several weeks prior to market to give them a characteristic green fringe colour and fine taste), producers have installed cooling equipment. It is costly, but very effective.

Better use of water and new "in-pond" production systems in inland systems

In the German länder of North Rhine – Westphalia, the Working Group on Water (LAWA) and the Federal/Länder Working Group on Climate Protection and Climate Adaptation in Agriculture, Forestry, Fisheries and Aquaculture (BLAG ALFFA) are working on a number of measures to optimise water use. These include pond interconnection systems, summering of ponds, shading and irrigation management. Shading is achieved by covering raceways with a roof that is covered by photovoltaic panels. The energy produced can be channeled towards water heating/cooling and other energy requirements. In periods of drought or scarce water at the source (spring) without enough water to fill the whole system, fish production can be alternated with land plant production for example buckwheat, that grows quickly on the natural fertilizers present in the pond substrate or, as an example in Saxony, one full pond is stocked instead of two half-empty ones.

Other measures under discussion are the increased multiple use of partial recirculation systems, and the reduction in water demand through the use of climate resilient species and strains. An EMFF funded Aquaculture Network was created to provide advice to SMEs on a case-by-case basis in the management of water use.

5.4 Infrastructure and system development

In many central and eastern European countries, new combined systems (in-pond raceway and/or tank-pond systems) can provide safer and better controlled juvenile production in the intensive part of these systems. The combined systems can also offer climate adaptive solutions by the intensive production of new species.

In Denmark, new systems are being tested for shellfish culture in Denmark, such as a height-adjusted modular mussel farming system that can be submerged on demand to avoid 1) surface weather conditions, such as storm, ice, etc., or 2) predators e.g., eider ducks.

5.5 Location planning and relocation

Background/Challenges

Changes in the water quality (physical and chemical) of aquaculture production sites can affect productivity in various ways (e.g. poorer growth, increased FCR, fish welfare, susceptibility to disease or parasites, etc.). The ultimate impact may be that the site will no longer be appropriate to produce species.

Other climate effects (such as increased storm occurrence, increased blooms of algae or jellyfish or increased fouling) do not necessarily mean that the whole site/area is no longer suitable for the production of species, but may require additional zones within it where fish could be moved to avoid mass mortality.

Other sites may be partially or even completely "lost" due to longer term climate-related occurrences such as coastal erosion, infiltration of wetland and lagoon areas, drying up of riverbeds or sources, or changes in the quality of borehole water.

In this context, an opportunity lies in the potential of farming the current species in new locations. This could help to expand production, with new areas and new sites being increasingly optimal for production.

Proposed solutions/Adaptation measures

Marine aquaculture in the EU is already moving towards expansion away from sites that are considered as being fragile (for example, due to water depth, seasonal temperature fluctuations) to those that have more stability (deeper water, "offshore", higher water flow and exchange rates). This is being accompanied by the use of larger and deeper cages and a host of technologies to better control, predict and manage production systems. The culture of multiple species in the same area (i.e. Integrated multi-trophic aquaculture - IMTA) is also considered as a solution to climate-induced environmental change, with the extractive species absorbing excess nutrients.

For inland production, the focus is on maintaining the quantity and quality of input water, but using less water more efficiently and/or reducing losses. Many MS have prioritised in their MNSPAs the move towards a partial or full recirculation of water. In addition, fully land-based production in RAS systems is being considered to decouple environmental interactions from production.

The AAM Guidance Document on "Access to marine space" provides examples of good practices and various MSP tools to identify AZAs and continued MSP should consider additional sites for the future production. The AAM is also currently producing a Background Paper on "Access to space and water for inland aquaculture." [31]

As part of the set of Copernicus Marine Service tools, PerfeCt - Performance of Aquaculture under Climate change[32] is an approach to answer the 'What if?' question when establishing and/or adapting aquaculture sites in the light of climate change.

This modular web application integrates a process-based modelling of fish growth, which builds upon the Dynamic Energy Budget theory. It also includes an innovative index to identify vibriosis disease risk. It is incorporated in the GIS framework to estimate relative changes of three simple aquaculture performance factors: time-to-market, food conversion ratio, and disease risk. By doing so, the application transforms science-based results into easily accessible and understandable information useful for aquaculture managers, investors, and policy makers.

It mainly contributes to:

- Help stakeholders ascertain future conditions relevant to aquaculture.
- Provide predictions for a range of commercially important species and range of climate change scenarios.
- Assist in the selection of existing aquaculture sites or a 10x10km coastal area of interest (currently in the Mediterranean Sea).

[31] See https://aquaculture.ec.europa.eu/knowledge-base/materials-developed-aam

[32] See https://marine.copernicus.eu/services/use-cases/perfect-performance-aquaculture-under-climate-change

5.5 Location planning and relocation

Examples of good practice in EU Member States and other countries

According to the answers to the AAM survey, producer organisations and associations in Croatia, Estonia, Malta, and Slovenia see new farm locations as an opportunity. In particular, the producer cooperative EAVÜ in Slovenia is using a service provider to assess options for farm relocation and a disease prevention plan.

In Germany, the Untere Fischereibehörde des Landes Berlin (Lower Fisheries Authority of the State of Berlin) has invested in aquaponics systems to avoid climate effects and use a combined species production system for fresh locally available vegetables. "Urban aquaponic farming" is an example of location planning that can future-proof and tailor-make fresh consumer products very close to the market. For example, a company in Berlin produces fresh basil plants in plastic-free packaging. The company has already used its technology to develop sites (rooftop farms) in Bad Ragaz (Czechia) and Brussels (Belgium).

A recent study by Pereira *et al*. (2023) has developed the use of a numerical model as a tool to assess the impact of climate change on aquaculture site selection in a temperate estuarine system (the Sado estuary in Portugal). A Delft3D model shows good accuracy in predicting local hydrodynamics, nutrient transport, and water quality. Two simulations for the historical and future conditions were performed to establish a Suitability Index capable of identifying the most appropriate sites to exploit two bivalve species (one clam and one oyster), considering both winter and summer seasons. The estuary's northernmost region presents the best conditions for bivalves' exploitation, with more suitable conditions during summer than winter due to the higher water temperature and chlorophyll-a concentrations. Regarding future projections, the model results suggest that environmental conditions will likely benefit the production of both species due to the increase in chlorophyll-a concentration along the estuary.

In Greece, a Decision Support Software (DSS) has been developed (ClimeGreAq) (Stavrakidis-Zachou et al., 2021) in collaboration with stakeholders. The DSS simulates and visualizes effects of climate change on fish and farm economics and may be used by stakeholders including farmers, producer organizations, regional administrations, and national authorities to support decision-making on questions ranging from selecting appropriate farming locations, to designating zones for aquaculture activities, to developing national climate adaptation plans.

5.6 Management of the introduction of non-native species

Background/Challenges

As climate effects intensify, genetic selection of existing species or the introduction of new species better adapted to environmental conditions is an option that many operators and MS are investigating. In most cases, this diversification is based on native species to that area or water basin. However, if the new species to be introduced is non-native, then legal requirements need to be met.

EU Regulation 708/2007 establishes a framework governing aquaculture practice in relation to alien and locally absent species to assess and minimise the possible impact of these and any associated non-target species on aquatic habitats and in this manner contribute to the sustainable development of the sector.

EU Regulation 1143/2014 covers the prevention and management of the introduction and spread of invasive non-indigenous species, providing a list of invasive non-indigenous species of concern for the EU and a set of measures to prevent, minimize and mitigate the adverse impacts of the species included in the list on biodiversity and related ecosystem services and on human health and the economy.

Proposed solutions/Adaptation measures

The main problems of the introduction of non-indigenous species are biosecurity risks, negative impacts on native species and changes to the ecosystem functioning through habitat alteration, predation, and disease transmission (including the introduction of new pathogens or parasites). Local impacts in sea basins or inland systems will have wider scale implications, given the complexity and interconnection of aquatic ecosystems.

To provide guidance on these introductions for the Mediterranean Basin, the General Fisheries Commission for the Mediterranean (GFCM) of the Food and Agriculture Organization of the United Nations (FAO) produced, in 2023, guidelines on principles and minimum common criteria to address the challenges.

The guidelines integrate a review of relevant documents, peer-reviewed articles and information received from aquaculture experts, researchers, and practitioners from Mediterranean and Black Sea countries. The data and information gathered were analysed to formulate and share best practices as well as practical recommendations for implementation. The guidelines are based on national and supranational legislation. They cover institutional elements (national capacity, competent authority, and advisory committee), application for authorisations, and risk-management measures. An example template for application for authorisation is included in annex to that document.

The guidelines recommend a unified ‘reference’ method or system for the classification and scoring system of the risk/impact of non-indigenous species. They suggest the EICAT framework (Blackburn et al. 2014 and Hawkins et al. 2015) or the Harmonia+ rating system (D’hondt et al. 2015), which provide clear guidance for scoring the impact of species introductions on biodiversity in risk assessments.

For the intended introduction of new, non-native species for aquaculture as an adaptation measure to climate change effects, enhanced national infrastructure and capacity requirements maybe needed for quarantine, health certification, disease reference laboratories, surveillance and monitoring programmes, effective enforcement capacity, effective biosecurity measures and trained staff.

Examples of good practice in EU Member States and other countries

The following examples are taken from the FAO/GFCM guidelines:

Quarantine measures

- The severity of quarantine should be proportional to the estimated level of risk, which is a function of the source. First-time introductions require stringent quarantine measures.
- The duration of quarantine should be indicated in the authorisation and may vary depending on the time required to complete the relevant health screening procedure. Non-

indigenous species should be kept in quarantine long enough to identify all non-target species and confirm the absence of pathogens or diseases.
- In the case of non-routine movements, aquatic organisms should be placed in a designated quarantine facility for the purpose of constituting a brood stock. Only the progeny of the introduced aquatic organisms may be used in aquaculture facilities and subsequently farmed.
- Adult specimens may be released into aquaculture facilities provided that it is scientifically evident that organisms do not reproduce in captivity or are fully reproductively sterile and where the absence of potentially harmful non-target species has been proven.

Contingency plans

For non-routine movements and pilot release studies, the contingency plan describes the measures to be taken to avoid unintentional release of the aquaculture organism, at any stage of its life, as well as any other associated organisms (for example, non-target species, pathogens, or parasites). The plan should be developed in case organisms or pathogens escape from quarantine or a serious pathogen is not detected during quarantine and is released into aquaculture facilities or the natural environment. Its main purpose is to facilitate a rapid response to restrict the spread and increase the likelihood that pathogens can be contained and eradicated.

If such an (escape) event occurs, the contingency plan should be implemented immediately and the authorization should be withdrawn, temporarily or permanently, by the competent authority.

Monitoring programmes

The objectives of monitoring programmes are to determine whether an accidental release has occurred and if disease or parasite infestations are present in the production facility; to evaluate the potential impact of the introduced organisms on the environment, ecosystem services and biodiversity; to assess the range of dispersal and containment and to identify unexpected events.

The monitoring programme should be:

- Based on the environmental risk assessment carried out prior to the release of organisms into aquaculture facilities and endorsed by the advisory committee.
- Customised for each introduction, according to species, potential dispersal range and geographic location.
- Used to confirm that diseases have not spread to new environments and, in cases where pathogens were present, but not detected during quarantine, to help minimize their impacts.
- Performed by a body appointed by the competent authority in three phases - baseline monitoring study prior to introduction, continued monitoring after release into aquaculture facilities; and longer-term monitoring following the scale-up of farming activities.

It is recommended that the duration of monitoring should be at least two years or at least one complete generation cycle of the species concerned.

Most MS producing non-native species are doing so in RAS, which not only offer the controlled conditions required for growth, but also the physical barrier to avoid interaction between the cultured species and its environment. Species that are currently being produced include pikeperch, African catfish, tilapia, and shrimp.

6. KNOWLEDGE GAPS & INDUSTRY/POLICY RECOMMENDATIONS

6.1 Research needs

While more and more knowledge is being generated on the specific climate change effects on aquaculture, there are still gaps to be filled. Knowledge gaps for cold water marine aquaculture of fish and shellfish were reviewed by Collins et al. (2020) and the list below includes these and complements them by needs outlined during the CEN workshop mentioned in Chapter 4 and by stakeholders and experts at the EU Aquaculture Workshop in Brussels in October 2023.

Forecasting and monitoring

- Monitoring of abiotic and biotic indicators for all species production.
- Improved resolution of satellite-based models to be relevant for aquaculture operations (coastal and inland).
- More knowledge on Harmful Algal Blooms including environmental drivers for their formation, AI-assisted detection, their biology and more precise understanding of their effects.

Environmental assessment

- Effects of climate change on the environmental impacts of aquaculture – e.g., assimilative capacity of receiving water bodies, including impacts at potential offshore sites.
- Information on offshore environment/ecosystem and potential impacts of climate change and ocean acidification on the sustainable growth of offshore aquaculture.

Adaptive capacity of farmed species

- Primary research (physiology, immune system and health status) on tolerance and optimum range for various (and combined) climate stressors, especially for lesser studied species and emerging ones.
- Development of models for forecasting the growth, heat consumption and feed efficiency of aquaculture species at shifted temperature and acidification regimes.
- Development of in situ diagnostic tools for welfare status.
- The synergistic effects of climate change and ocean acidification and the effect of fluctuating (compared to continuous) exposure to these impacts on settlement (shellfish) as well as growth and survival of farmed shellfish species.

Disease management

- Effects of climate change and ocean acidification on pathogens, disease development and antimicrobial resistance, and on complex disease outcome.
- Further development of models that can predict pathogen emergence and disease development with changing environmental parameters caused by climate change.
- Development of vaccines for emerging new pathogenic bacteria and viruses.
- Better understanding of the effects of increased antibiotics utilization on pathogen and disease development in the context of increasing antimicrobial resistance.

Feeds

- Better understanding of the effects of feed additives (vitamins, yeast) and immunostimulant products (including microbial derived substances), particularly during winter and in early spring.

Non-native species

- Better understanding of changing environmental factors on the invasion, establishment and spread of a range of relevant non-native species (and their associated organisms), and on their physiology and health.

- Assess the risks to the industry, which is increasingly impacted by native species acting invasively (for example the proliferation of sea squirts on bottom mussel beds, or blue crabs on clam beds) which makes harvesting and management very difficult.

6.2 Industry Adaptation Measures Recommendations

The following adaptation measures are recommended to be enacted by Industry producer organisations, other sector operators and by individual companies. These can also be included in MS adaptation programs with support measures (e.g. financial, research, etc.) to the industry.

- Develop breeding programmes (including mass and family selection in shellfish) for all EU species focused on increasing tolerance to climate change effects.
- Monitor fish and shellfish health, performance, welfare and behaviour (using real time / in situ tools):
    - Daily measurements of dissolved oxygen and temperature.
    - Improved understanding of fish growth rates.
    - Data records on mortalities.
    - Data records on disease related mortalities (>500 individuals).
- Develop and adopt more robust (and automated) infrastructure for:
    - Feeding.
    - Movement of fish.
    - Cleaning processes in line with increased biofouling.
- Increase and further develop the use of aerators and other oxygen supply techniques.
- Apply adequate biomass management (where possible) to compensate for seasonal temperature profiles.
- New and improved systems (cooling, recirculation, etc.) for shellfish production.

6.3 Policy recommendations

The following adaptation measures should be adopted by MS and/or specific competent authorities:

- Identify how policy and legislation can better support climate change adaptation initiatives in aquaculture and therefore provide more targeted support.

- Allocate funds in support of all research gaps that are considered as a priority for that country in consultation with aquaculture stakeholders and scientific experts.

- Establish or upgrade monitoring programmes (with standardised format/content and easy access to pooled results for operators, on:

    - Site physio-chemical indicators of water quality (all sites).
    - Phytoplankton/zooplankton in ponds.
    - Other appropriate environmental monitoring that provides the required data on climate change.
    - Husbandry indicators, including data on individual sizes; length of production cycles; stocking rates; winter biomass losses; mortality and disease outbreaks.

- Include shellfish as a bio-indicator of the quality of shellfish waters in respect to not only health and survival, performance, and growth but also reproductive capacity, and follow reproductive cycles continuously.

- Develop species-specific programmes with producers to help national and/or regional governments to adapt regulations to the new conditions created by climate change and for the sector to ensure production.

- Integrate aquaculture spatial planning into the existing framework for Maritime spatial planning) and Inland Planning, including:
    - Identification of sites for potential relocation or reallocation of aquaculture activity by the further identification and establishment of AZAs where critical affecting parameters of climate change are less abrupt and hence allowing aquaculture production to adapt to changes more easily.
    - Adaption of legislation/licensing thresholds to finer scale and with a flexible framework for the designation of new farm sites or aquaculture zones, combined with simplification of the licencing procedure.
    - Explore and promote co-location with other marine/maritime activities (for example aquaculture and wind farms).
    - Continuous synergies in the management of Marine Protected Areas and the compatible forms of aquaculture production that can be developed within them.

- Expand financing of climate adaptation measures, including support for the transition required by the sector to reinforce its resilience, productive and environmentally stable credentials.

- Further develop national and/or European development of insurance for climate-related events.

- Keep aquaculture high on the list of EU and MS priorities concerning policy, strategy and actions related to climate change adaptation.

7. CONCLUDING COMMENTS AND RECOMMENDATIONS

This Guidance Document has the principal objective to support EU Member States and the industry in creating and updating Climate Adaptation Plans for aquaculture.

To do so, it presents effects (both negative and positive) that climate changes can have on European aquaculture. It also describes a detailed process for developing a Climate Adaptation Plan and provides examples of good practices for several climate adaptation measures. Finally, it details some of the existing knowledge gaps and policy recommendations needed to adapt to climate changes.

Several concluding comments and recommendations are listed here:

- There is no formal CAP in any MS at present. Climate change effects and adaptation measures are mentioned in most MNSPAs (see Annex III), but at differing levels of detail.

  It is highly recommended to use a stakeholder-driven approach to prepare a CAP before the next MNSPA, so as to further detail the specific priorities, adaptation measures and supporting policy or financial instruments. This may be preceded or accompanied by a national aquaculture environmental or carbon footprint analysis to identify strategic options.

  CAPs should take into account intra-national variability of climate change effects and adaptation measures should be accordingly tailored to the specificities of a region and the type of aquaculture production therein.

- While climate effects are generally classified into short-term impacts (such as extreme weather events, access to fresh water, disease, parasites, predators, and harmful algal blooms that can have an immediate effect on production) and longer-term impacts associated with changes in water temperature, salinity, acidification, oxygen content and sea level rise, there are regional examples that show that this is actually a time continuum which has long begun, with numerous impacts already affecting production to differing extents.

  MS should put in place the necessary measures to support the sector to implement the CAP. These may include financing of infrastructure improvements, prioritised and targeted research, improvement of insurance. They should also implement agreed adaptation measures themselves, as identified through the CAP process.

- Technology and data integration provide excellent prospects for better real-time and 'holistic' environmental monitoring and forecasting, as well as improved production infrastructure.

  Both should be prioritised for rapid development and deployment. Data integration is of high importance to individual operators, but can also provide enhanced accuracy of national monitoring, with the specific identification of climate change monitoring indicators and their inclusion in MS data collection. The EU has proposed indicators for Climate Adaptation, for example the Bioeconomy Monitoring System Indicator Update (EC JRC 2023).

  MS are encouraged to select the most suitable indicators that can be used for the monitoring of CAPs, to measure progress in their implementation.

- Despite climate-related projects supported by the EU, there are still knowledge gaps that need to be filled. One of the more important gaps is the combined and/or cumulative effect of 'individual' parameters and stressors and the assessment of opportunities that climate change might offer. Another example of required adaptation measures is shown in the factsheet on breeding. There is no clear good practice on breeding for resilience and current strains are generally considered as not being sufficiently resilient.

National Research programmes and structural funding could focus on specific research to support the needs of their sector and to support the rapid development of appropriate adaptation measures. Industry associations and breeding companies are encouraged to focus on selection of climate-related traits, including overall robustness of juveniles, temperature tolerance and disease resistance.

The EC 'Strategic Guidelines for a more sustainable and competitive EU aquaculture' clearly identify the need to adapt to and mitigate the effects of climate change to build resilience and competitiveness for the aquaculture sector. While it was not the focus of this Guidance Document, aquaculture also has great potential to mitigate climate change, though the ecosystem services it provides. This could be achieved through nature-based coastal protection, buffering of floods and droughts through pond or wetland management as well as considering the potential for carbon sequestration through shellfish and algal culture.

As stated in Annex to the EU Strategic Guidelines, MS are encouraged to develop sector-specific national, regional, transnational, or sea-basin climate adaptation plans consistent with their national strategies and plans. Adaptation and mitigation measures therefore need to be documented in more detail than is the case at present.

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9. ANNEXES

ANNEX I: About the Aquaculture Assistance Mechanism (AAM)

The EU Aquaculture Assistance Mechanism (AAM) is a consortium under a service contract to support the Commission, Member States, the aquaculture industry, and other stakeholders in the implementation of the "Strategic Guidelines for a more sustainable and competitive aquaculture for the period 2021-2030", through the provision of logistic, administrative, and technical assistance, as well as one-stop-shop for knowledge and good practices about sustainable aquaculture in the EU.

The AAM is jointly managed by the Directorate-General for Maritime Affairs and Fisheries of the European Commission (DG MARE) and the European Climate, Infrastructure and Environment Executive Agency (CINEA).

The consortium is coordinated by NTT DATA in partnership with Aristotle University of Thessaloniki, SCOPE - Intrasoft, the European Aquaculture Society (EAS) and the European Aquaculture Technology and Innovation Platform (EATIP). The Service Contract started in June 2022 and will run until June 2024.

The website https://aquaculture.ec.europa.eu/ is the portal of the AAM with an extensive knowledge base containing:

- EU legislation and relevant international instruments
- Guidelines
- Good practices and experiences
- Projects
- Reports
- Scientific papers and publications
- Learning material
- Materials developed by the AAM
- Member States area

It also has a funding section, which provides an overview of EU open calls for proposals and tenders in the field of aquaculture, as well as an area dedicated to aquaculture-related EU events. Finally, the AAM website also has a country information section.

ANNEX II: The EU Climate-ADAPT portal

The European Climate Adaptation Platform Climate-ADAPT was developed by the European Commission and the European Environment Agency (EEA) with the aim of supporting Europe in its adaptation to climate change. The portal provides users with data and information on:

- Expected climate change in Europe.
- Current and future vulnerability of regions and sectors.
- EU, national and transnational adaptation strategies, and actions.
- Adaptation case studies and potential adaptation options.
- Tools that support adaptation planning.

Climate-ADAPT structures the data and information in different sections to facilitate its access for users. The latter are:

- A database including different 58 adaptation options, 118 case studies, 141 guidance documents, 87 indicators, 211 information portals, 35 videos, 137 organisations, 952 publications and reports, 519 research and knowledge projects and 94 tools.
- EU Sector policies on Marine and Fisheries, Agriculture, Biodiversity or Water Management among others.
- Country profiles of EEA members.
- Cases studies on key aspects in the implementation cycle of adaptation measures.
- An Adaptation Support Tool.

ANNEX III: Overview table of aquaculture measures included in MS Multi-annual National Strategic Plans for Aquaculture

The following table compiles, for each Member Sate, the main adaptation measures of the aquaculture sector included in their MNSPAs.

Member State	Information derived from MNSPA
Austria	Chapter 2: Objectives for domestic aquaculture and inland fishing -Subchapter 2.1 (pp. 23-24): Adaptation of the aquaculture and fisheries sector to climate change ("Fit for Climate Change") and further orientation towards sustainability and biodiversity. Chapter 3: Measures -Subchapter 3.3 (pp. 31-32): Measures to adapt to climate change, maintain or increase biodiversity, and ensure sustainability and resource conservation in production, processing, and marketing. From the MNSPA summary: In order to adapt to climate change, the testing and introduction of adapted high quality restocking fish species for aquaculture should be supported. However, attention must be paid to the risk of spreading potentially invasive species. In the case of existing salmonid producers and in view of the emerging climate change, opportunities should be created to provide fish with the necessary water in emergency situations during extreme weather conditions (such as floods, extreme heat periods). For example, by halving the residual water supply in the short term or recovering the wastewater as residual water.
Belgium	Investments and innovative research projects will be eligible for support to the extent in which they contribute to maintaining or increasing aquaculture production. Specifically for the Walloon context, the above-mentioned financial support will focus on modernising and implementing technological tools to reduce dependency on soil and climate conditions (e.g., through partial recirculation or cooling of water), or to switch to other and less sensitive species that are more resilient to climate change. The more artisanal production methods remain highly dependent on external events. Public aid can be provided from Wallonia, outside European funding, as compensation under certain conditions.
Bulgaria	Build/adapt reference tools for modelling the impacts of marine and inland farming on the environment and provide for the recognition of the results of these models by the administration.
Croatia	Increase investment in efficient and sustainable technologies in aquaculture. In this context, priority will be given to projects aimed at investments in environmentally sustainable intensification of aquaculture production systems, combined intensive-extensive aquaculture systems, RAS or IMTA, as guarantees of controlled farming conditions with shorter production cycles that also ensure a safe product. The Climate Change Adaptation Strategy of Republic of Croatia (OG, No 46/20) identifies fisheries and aquaculture, as the one of the sectors that are expectedly most exposed to climate change and defines climate change adaptation measures for fisheries and aquaculture. https://mingor.gov.hr/o-

Member State	Information derived from MNSPA
	ministarstvu-1065/djelokrug/uprava-za-klimatske-aktivnosti-1879/strategije-planovi-i-programi-1915/strategija-prilagodbe-klimatskim-promjenama-republike-hrvatske/8351
Cyprus	Actions aimed at: ○ Promoting research and improving knowledge on understanding the impacts of climate change on aquaculture and therefore increase resilience. ○ Implementing measures to strengthen the resilience of aquaculture in response to extreme weather conditions. ○ Diversification with species resilient to climate change.
Czechia	Chapter (9.7), pp. 137-138. The implementation of fisheries activities will be reflected in the achievement of some objectives, such as climate adaptation and risk prevention and management. To achieve this objective, it includes a list of activities (Table 29- p. 137): ○ Implementation of the approach to combat drought implemented by the Ministry of the Environment and the Ministry of Agriculture. ○ Aid for the construction, rehabilitation, reconstruction and dredging of fishponds and water reservoirs. ○ Support for the removal of emergency situations on ponds and water reservoirs. ○ Support for the elimination of flood damage to ponds and reservoirs. ○ Compensation for damage caused by climate change (drought, floods).
Denmark	With the agreement on the Maritime, Fisheries and Aquaculture Programme 2021-2023, the 'Green Transition Aquaculture' theme is dedicating: - DKK 21,0 million aid for investments in climate solutions and purification technology to reduce the climate footprint of the aquaculture sector and emissions of nitrogen, phosphorus, and organic matter to the surrounding environment.
Estonia	Chapter (3.4), pp. 16-18. Environmental conditions and adaptation to climate change. It highlights the challenges that agriculture producers face and the importance of climate change adaptation and measures that are necessary in order to adapt and increase the resilience of the agriculture sector. Some of the measures exposed are the contribution to investments that encourage environmentally sustainable production, including the deployment of green technologies and the more efficient use of resources; the reduction of the excess nutrients in the aquatic environment; or the creation of opportunities for synergistic solutions, regarding to maritime planning and environmental aspects.
Finland	○ Supporting the development of sector-specific national, regional, transnational, or sea-basin climate adaptation plans consistent with national strategies and plans, as well as the corresponding CEN standard. ○ Supporting training on climate adaptation and resilience for people working in the aquaculture sector. ○ Supporting climate change mitigation in the aquaculture sector.

Member State	Information derived from MNSPA
	○ Implementing justified measures to enable the aquaculture sector to adapt to climate change and reduce its climate impact.
France	Build/adapt reference tools for modelling the impacts of marine and inland farming on the on the environment and provide for the recognition of the results of these models by the administration.
Germany	Adaptation and Mitigation Measures: ○ Reduction of effects of rising temperatures on the functioning of aquaculture facilities. ○ Mitigating climate related deficiencies in water quality in carp farming and trout production. ○ Technology (oxygenation, effluent treatment, warning systems, etc.); this requires targeted support schemes for the technical development of farms, training and further training in technical aquaculture and support for technical assistance for the conversion of existing facilities. ○ Partial circulation of rearing water. Support for refurbishment measures to cover sub-circuits. ○ Adapted water management in ponds interconnected systems. ○ Production of corresponding guides, e.g., for multi-annual pond spraying. ○ Implementation of targeted research projects in cooperation with practical operators to adapt to changed environmental-conditions and use of climate-resilient fish strains. ○ Reduction of the "ecological footprint" of the Aquaculture through Energy saving and increasing sustainability. ○ Production of guidance on how to reduce the ecological footprint in aquaculture.
Greece	Chapter (3.3.5), pp. 75- 76. It indicates that the sector will have to adapt as far as possible to the uncertainty and the potential risks of climate change, by planning actions that mitigate and/or eliminate negative impacts or exploit the opportunities presented. The actions are aimed at: ○ Creating of a database of research findings on the impact of climate change on aquaculture. ○ Developing studies and pilot projects to improve the technical characteristics of the facilities (cages, anchorages) in order to be more resilient to extreme weather events. ○ Developing abiotic parameters control and regulation systems (e.g., temperature, water circulation rates) in marine fish farms in floating cages. ○ Promoting a medium-term plan for the gradual "re-siting" of units from vulnerable areas to places less affected by climate change, with the establishment of new Aquaculture Development Areas with new plant locations suitable for mitigating the effects of climate change. ○ Using renewable energy technologies and implementing good practices such as improving the quality of fish feed and optimising feeding rate. ○ Implementing prevention and biosecurity measures to maintain the health of farmed organisms. ○ Developing of forecasting models and decision support tools.
Hungary	The most important tool of developing pond aquaculture and combined intensive-extensive aquaculture system with a special focus on climate resilience is the measure 'Support for environmental investments in aquaculture and fish processing', as well as the measure 'Support for

Member State	Information derived from MNSPA
	maintaining the natural value of fish ponds' contributing to the maintenance of ponds. Another important tool to improve environmental sustainability and climate neutrality is innovation in the sector (measure "Innovation and technology development in aquaculture and fish processing"). Finally, the measure "Improving the legal framework for fisheries and aquaculture management, administrative simplification" supports the preparation of a sectoral climate adaptation plan based on broad consultation and taking into account the latest models and scientific evidence, which will provide a coherent framework for measures aiming at climate neutrality in the sector and underpin their effective implementation.
Ireland	Collaborate nationally and internationally to understand how aquaculture systems contribute to carbon sequestration and how this can be applied commercially. Notably: o Encourage opportunities for low trophic aquaculture species that can contribute to a low carbon economy. o Mainstream opportunities to reduce the carbon footprint of Irish aquaculture though the wider adoption of IMTA and other low carbon technologies. o Assist the aquaculture supply chain to reduce its carbon footprint in the life cycle. o Include climate change variables in environmental monitoring data collection. o Support projects with strong climate mitigation and adaptation characteristics.
Italy	Among the strategic actions, (Table 6.8) highlights the issues and expected results of the measures for adaptation of aquaculture to climate change (p.62). Firstly, the critical issues are the following: lack of knowledge on the effects of CC on aquaculture; difficulties in analysing vulnerability to CC in relation to the different production systems; need for collaborative and multidisciplinary research. Secondly, the expected results are to increase knowledge base and technical and scientific reports on aquaculture and climate change; and increase the number of mitigation actions/actions to improve the life cycle and energy efficiency of companies.
Latvia	o Aquaculture providing environmental services. o Tackling the negative impacts of climate change. o Supporting pond farms that offer environmental services and whose production efficiency is influenced by the protection requirements of fish-breeding birds and animals, as well as the creation and development of new organic farms. It is necessary to continue to provide public support to cover income foregone or additional costs for enterprises.
Lithuania	o Support the implementation of measures to reduce environmental pollution and technological innovation. o Support the implementation of energy efficiency measures and to promote the use of energy from renewable energy sources. o Support the implementation of adaptation measures. Energy consumption and carbon emissions from production, transport and processing must be reduced as much as possible.

Member State	Information derived from MNSPA
	Aquaculture also has significant mitigation potential. Well-managed aquaculture can help preserve ecosystems such as wetlands. These ecosystems provide protection against climate-change impacts such as sea-level rise and floods. This type of aquaculture should be promoted, as well as aquaculture providing circular economy, energy efficiency and ecosystem services.
Luxembourg	N/A
Malta	It proposes two actions to achieve the objective of Climate Change Adaptation and Mitigation: ○ Increase investments in R&D and conduct research both on the effect of Climate Change on the local aquaculture industry and on sustainable genetic technologies to create farmed types that are resistant to, can adapt to, or can minimize the impacts of climate change, for example able to withstand acidification, salinization and temperature and precipitation changes. Following Aquatic Advisory Council recommendations, research will focus also on alternative production species such as microalgae and macroalgae, to contribute towards increased sustainable production by minimising the carbon footprint of fishmeal-based feeds. ○ Integrate climate-proofing, technological and financing innovations that increase adaptation and resilience of the sector, including innovations in institutions, emissions reductions and renewable energy systems such as co-location of new aquaculture sites with offshore infrastructures (e.g., offshore oil rigs, wind and wave energy facility installations or photovoltaic power generation), or using renewable energy heating and cooling systems and water pumps, or hydropower and other aquatic based energy systems that exploit the energy potential of tides, currents, waves and wind.
Netherlands	The shellfish sector could develop a climate change adaptation plan in order to be prepared for the possible consequences. The CERES project can provide support in this matter.
Poland	As a challenge for inland fisheries and aquaculture, it was identified: ○ Preparing the sector for climate change by drawing up industry plans that take into account the specificities of the different types of domestic aquaculture production and by drawing up and implementing good practices in response to climate change and practices relating to the welfare of farmed fish. Needs highlighted: ○ Tackling the effects of climate change and reducing CO2 emissions in fish farming, including investments in energy efficiency and diversification of energy sources, including through the use of RES. ○ Moving towards a climate-neutral economy through the introduction of RAS.
Portugal	○ Encourage the aquaculture production of algae (macroalgae, microalgae) as they play an important role in capturing carbon dioxide from the atmosphere. Also, they exert a "buffer effect" and play a role in combating ocean acidification. ○ Promoting sustainable aquaculture in managed areas coexist with areas that need to be protected. ○ Optimisation of aquaculture production units through the implementation of RAS, IMTA and aquaponics.

Member State	Information derived from MNSPA
	○ Promoting water quality improvement through the treatment of effluent using biofilters, algae and bivalves placed in the channels or decantation tanks. ○ Adopt measures that will contribute to reducing the use of alien species alien species in aquaculture.
Romania	○ Identification of the effects of climate change in aquaculture. ○ Devolvement of hatchery / nurseries.
Slovakia	○ Construction and reconstruction of aquaculture facilities, including improvement measures. ○ Support to repair damage caused by climate change (floods, drought, hail, strong wind…). ○ Align the objectives of the water policy concept for 2021-2030 with the prospects for 2050 of the Ministry of the Environment of the Slovak Republic with those in aquaculture. ○ Preparation of workshops for aquaculture actors on climate change adaptation and mitigation.
Slovenia	A sectoral vulnerability assessment and possible solutions and adaptations to climate change will be prepared in cooperation with other ministries within the Strategic Framework for Climate Change Adaptation in the Republic of Slovenia. Under the PESPRA 2021-2027 a study will be financed on the options for a transition to organic aquaculture. Once the results of the study are ready, decisions will be made on to what extent the support to the transition to organic aquaculture could be given.
Spain	It includes a chapter on Climate Change (page 57), and it highlights the risks associated to it (biological, economic, and social) and some actions to address them (pages 144-145). In the adaptation to climate change, it is necessary to improve the resilience of the aquaculture sector. To achieve this, it proposes three actions: diagnosis and risk assessment, adaptative strategies to climate change, and risk management. In the contribution to climate change mitigation, it points out two actions: analysis and quantification of effects; and climate mitigation and adaptation services.
Sweden	Chapter (5.7)- pages 52-56. It offers an assessment of the national situation (the needs for adaptation to climate change), measures envisaged (such as 'Digitalisation of Swedish aquaculture production', 'Development of production techniques and species' and 'Nutrition and feed development) and objectives and indicators (increase the number of extractive aquaculture and reduce energy consumption).

ANNEX IV: Example Risks/Opportunities matrices from H2020 Climefish

In its various case studies, the CLIMEFISH project produced visual matrices showing the risks and opportunities of climate effects that were developed through stakeholder consultation. Some of these are presented here for reference and can be used as templates for the development work of a CAP. They include:

- Hungary: Pond Farming
- NE Atlantic: Marine Aquaculture
- Greece: Marine Aquaculture
- Spain (Iberian Upwelling): Shellfish Aquaculture.

Each table contains categories, associated drivers, and potential impact, with of the risks or opportunities. In addition, they show if this driver has been modelled, the degree of stakeholder consensus (traffic light colours with standard deviation) as well as the risk rating 2020, 2030 and 2050 under two climate scenarios. The last column shows the overall risk (considering all scenarios and timescales).

It should be noted that there are discrepancies in the some of the risk/opportunities presented and the risk ratings shown were not always agreed by all stakeholders. Furthermore, the climate scenarios date back four years and are already out of date, so these tables are more useful as models or templates to use in the development of a CAP, rather than providing actual opinion or assessment that can be used if this process were to be done today.

Table 5. Hungary: Pond Farming Risks

Identified climate-related risks in Hungarian pond production					RCP4.5			RCP8.5			Overall Risk (all scenarios and timescales)
Category	Climate Change Drivers	Potential Impact	Modelled? Yes/No	Stakeholder Consensus Std. Dev	Risk Rating 2020	Risk Rating 2030	Risk Rating 2050	Risk Rating 2020	Risk Rating 2030	Risk Rating 2050	Risk Rating
Biomass losses	Increased water temperature and extreme weather	Increased mortality owing to biotic stress	No	0.6	Moderate	Major	Severe	Moderate	Major	Severe	**Major**
Water use	Increased water temperature, changes in precipitation	Increased evaporation losses	Yes	0.6	Moderate	Major	Major	Moderate	Major	Major	**Major**
Pond food web	Increased water temperature	Increased phytoplankton production	Yes	1.4	Moderate	Major	Major	Moderate	Major	Major	**Major**
Water quality	Increased water temperature	Heightened risk for suboptimal and subcritical dissolved oxygen levels	Yes	0.0	Major	Major	Major	Major	Major	Major	**Major**
Water quality	Increased water temperature	Deterioration of inlet water quality	No	0.5	Moderate	Moderate	Major	Moderate	Moderate	Major	**Moderate**
Water quality	Increased water temperature	Increase presence of harmful bacteria	No	0.8	Moderate	Moderate	Major	Moderate	Moderate	Major	**Moderate**
Water use	Increased water temperature, changes in precipitation	Decreased water availability	No	0.6	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	**Moderate**
Management	Extreme weather events	Infrastructure deterioration	No	0.6	Minor	Moderate	Moderate	Minor	Moderate	Moderate	**Moderate**
Management	Increased water temperature	Increase costs of medical treatment	No	0.5	Minor	Moderate	Major	Minor	Moderate	Major	**Moderate**
Pond food web	Increased water temperature	Increased need of manuring	No	0.8	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	**Moderate**
Water quality	Increased water temperature	Polluted effluent water	Yes	0.5	Minor	Moderate	Moderate	Minor	Moderate	Moderate	**Moderate**
Pond food web	Increased water temperature	Increased presence of trash fish (food competitors)	No	1.0	Minor	Minor	Moderate	Minor	Minor	Moderate	**Moderate**
Biomass losses	Increased water temperature and extreme weather	Increase of predation from birds	No	1.4	Minor	Minor	Moderate	Minor	Moderate	Moderate	**Moderate**
Pond food web	Increased water temperature	Depletion of natural food resources available for carp	No	0.5	Minor	Minor	Moderate	Minor	Minor	Moderate	**Moderate**
Water use	Increased water temperature, changes in precipitation	Increase in water prices	No	0.5	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	**Moderate**
Biomass losses	Extreme weather events	Climate induced water turbidity threatening fry rearing	No	1.0	Minor	Minor	Minor	Minor	Minor	Minor	**Minor**
Biomass losses	Increased water temperature and extreme weather	Increased occurrence of escapees	No	0.5	Minor	Minor	Minor	Minor	Minor	Minor	**Minor**
Growth & feeding	Increased water temperature	Increased feed demand	No	1.0	Minor	Minor	Minor	Minor	Minor	Minor	**Minor**

Table 6. Hungary: Pond Farming Opportunities

Identified climate-related opportunities in Hungarian pond production					RCP4.5			RCP8.5			Overall Risk (all scenarios and timescales)
Category	Climate Change Drivers	Potential Impact	Modelled? Yes/No	Stakeholder Consensus	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating
				Std. Dev	2020	2030	2050	2020	2030	2050	
Pond food web	Increased water temperature	Increased zooplankton production	Yes	0.0	Moderate	Major	Major	Moderate	Major	Major	Major
Growth & feeding	Increased water temperature	Altered stocking and harvest strategies owing to extended growing season	Partly	1.2	Moderate	Moderate	Major	Moderate	Major	Major	Major
Growth & feeding	Increased water temperature	Increased individual growth rates and yields	Yes	0.5	Moderate	Moderate	Major	Moderate	Major	Major	Moderate
Pond food web	Increased water temperature	Increased phytoplankton production	Yes	0.6	Moderate	Moderate	Major	Moderate	Major	Major	Moderate
Growth & feeding	Increased water temperature	Increased feed demand	No	0.0	Minor	Minor	Minor	Minor	Minor	Minor	Minor
Pond food web	Increased water temperature	Increased presence of trash fish (prey fish for cultured carnivorous)	No	na	Minor	Minor	Moderate	Minor	Minor	Moderate	Minor

Table 7. NE Atlantic: Marine Aquaculture Risks

Identified climate-related risks in North-east Atlantic Salmon Aquaculture - South Region					RCP4.5			Overall Risk (all scenarios and timescales)
Category	Climate Change Drivers	Potential Impact	Modelled?	Stakeholder Consensus	Risk Rating	Risk Rating	Risk Rating	Risk Rating
			Yes/No	Std. Dev	2015 - 2025	2025 - 2035	2045 - 2055	
Biological	Increased heat waves	Inhibition of growth, increased mortality	Yes	0.53	Major	Severe	Severe	Major
Production	Changed hydrodynamics - eg. Temp, salinity, currents	Increased fouling	No	0.92	Major	Major	Major	Major
Biological	Increased water temperature	Regional and temporal changes in individual fish growth	Yes	0.83	Moderate	Major	Major	Major
Biological	Increased water temperature	Pathogen virulence, occurrence and severity, success of treatments	No	0.35	Moderate	Major	Major	Major
Socio-economic	Increased water temperature, extreme weather and temperature.	Higher feed costs due to higher Feed conversion rates	Yes	0.98	Moderate	Major	Major	Major
Socio-economic	Increase water temperature	Increase of feed prices	No	0.84	Moderate	Major	Major	Major
Biological	Hydrodynamic changes	Increased occurrence of harmful algal and jellyfish blooms	No	0.64	Moderate	Major	Major	Major
Socio-economic	Increased water temperature	Reduced quality of fish will lead to lower sales prices	No	0.64	Moderate	Moderate	Major	Moderate
Biological	Increase water temperature → changes in currents	Distribution and presence of pathogens and parasites	No	0.50	Moderate	Moderate	Major	Moderate
Socio-economic	Extreme weather, temperature	Conflicts for space, relocation of farms problems	No	1.25	Moderate	Moderate	Moderate	Moderate
Production	Extreme weather events	Breakdowns, increase of escapees and infrastructure requirements	No	0.52	Moderate	Moderate	Moderate	Moderate
Socio-economic	Extreme weather events	Human safety issues	No	0.49	Moderate	Moderate	Moderate	Moderate
Socio-economic	Increase water temperature	Changes in salmon prices	No	na	No	Moderate	Moderate	Minor
Biological	Increased water temperature → reduced O2	Reduced growth and increased mortality	No	na	No	No	Moderate	Minor

Table 8. NE Atlantic: Marine Aquaculture Opportunities

Identified climate-related opportunities in North-east Atlantic Salmon Aquaculture - North Region					RCP4.5			Overall Risk (all timescales)
Category	Climate Change Drivers	Potential Impact	Modelled?	Stakeholder Consensus	Risk Rating	Risk Rating	Risk Rating	Risk Rating
			Yes/No	Std. Dev	2015 - 2025	2025 - 2035	2045 - 2055	
Socio-economic	Increased water temperature, extreme weather and temperature.	Change in feed costs due to change in Feed conversion rates	Yes	0.90	Moderate	Moderate	Moderate	Moderate
Biological	Increased heat waves	Inhibition of growth, increased mortality	Yes	1.07	Moderate	Moderate	Moderate	Moderate
Biological	Increased water temperature	Regional and temporal changes in individual fish growth	Yes	1.20	No	No	Moderate	Minor

Table 9. Greece: Marine Aquaculture Risks

Identified climate-related risks in Greek aquaculture					RCP4.5			RCP8.5			Overall Risk
Category	Climate Change Drivers	Potential Impact	Modelled?	Stakeholder Consensus	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating
			yes/no	Std. Dev	2020	2030	2050	2020	2030	2050	All scenarios and timescales
Biological	Increased water temperature	Increase presence of pathogens	no	0.64	Severe	Severe	Severe	Severe	Severe	Severe	Severe
Biological	Increased water temperature	Seasonal changes in growth and stocking timing	yes	0.58	Major	Major	Severe	Severe	Severe	Severe	Severe
Production	Increased water temperature	Increase of feed prices	no	0.98	Major	Major	Major	Major	Major	Major	Major
Production	Extreme weather events, changes in rainfall and droughts	Higher fluctuation of feed prices	no	0.98	Major	Major	Major	Major	Major	Major	Major
Biological	Increased water temperature	Inhibition of growth and increase of mortality	yes	0.93	Major	Major	Major	Major	Major	Major	Major
Ecological/environmental	Increase water temperature, changes in currents and water circulation	Increase of HABs and fouling	no	1.03	Major	Major	Major	Major	Major	Major	Major
Production	Extreme weather events	Suitability of farm sites	yes	1.22	Moderate	Major	Major	Moderate	Major	Major	Major
Biological	Increase water temperature and extreme weather events	Increased mortality	yes	0.89	Moderate	Moderate	Major	Moderate	Major	Major	Major
Ecological/environmental	Increased water temperature	Increase of organic discharge	no	0.93	Major	Major	Major	Major	Major	Major	Major
Ecological/environmental	Changes in currents and water circulation	Water quality deterioration, risk for anoxic conditions	no	1.27	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Biological	Increase water temperature and extreme weather events	Increased size variability	yes	0.45	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Ecological/environmental	Extreme weather events	Infrastructure damages	no	1.04	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Biological	Extreme weather events	Inhibition of growth	yes	0.00	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Identified climate-related risks in Greek aquaculture					RCP4.5			RCP8.5			Overall Risk
Category	Climate Change Drivers	Potential Impact	Modelled?	Stakeholder Consensus	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating
			yes/no	Std. Dev	2020	2030	2050	2020	2030	2050	All scenarios and timescales
Biological	Increase water temperature / extreme weather events	Shift of thermal window suitable for growth	no	0.50	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Ecological/environmental	Increased water temperature	Increased use of antibiotics	no	1.16	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Ecological/environmental	Extreme weather events	Increase of escapees	yes	0.71	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Production	Extreme weather events	Increase of feeding related costs	no	0.71	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Socio-economic	Growth irregularities driven by temperature increase and extreme weather events	Increase in variability of market prices	no	0.71	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Ecological/environmental	Extreme weather events	Decrease of farm accessibility	yes	0.92	Minor	Minor	Minor	Minor	Minor	Minor	Minor
Ecological/environmental	Increased water temperature	Increase of chemical leaching	no	0.90	Minor	Minor	Minor	Minor	Minor	Minor	Minor
Socio-economic	Variability of fisheries landings driven by temperature increase and extreme weather events	Increase in variability of demand for aquaculture products	no	0.00	Minor	Minor	Minor	Minor	Minor	Minor	Minor
Ecological/environmental	Increase water temperature and extreme weather events	Increase of predation	no	0.71	Minor	Minor	Minor	Minor	Minor	Minor	Minor

Table 10. Greece: Marine Aquaculture Opportunities

Identified climate-related opportunities in Greek aquaculture					RCP4.5			RCP8.5			Overall Risk
Category	Climate Change Drivers	Potential Impact	Modelled?	Stakeholder Consensus	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating
			yes/no	Std. Dev	2020	2030	2050	2020	2030	2050	All scenarios and timescales
Biological	Increased water temperature	Increase of biomass and production capacity	yes	0.52	Major	Major	Transformative	Major	Transformative	Transformative	Transformative
Biological	Increased water temperature	Seasonal changes in growth and stocking timing	yes	0.69	Major	Major	Transformative	Major	Transformative	Transformative	Transformative
Biological	Increase water temperature / extreme weather events	Shift of thermal window suitable for growth	yes	0.89	Major	Major	Major	Major	Major	Major	Major
Production	Increased water temperature	Increase of production	yes	0.89	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Socio-economic	Increase of biomass driven by temperature increase	Increase of employment	no	0.76	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Ecological/environmental	Increased water temperature	Increase of organic discharge	no	0.00	Minor	Minor	Minor	Minor	Minor	Minor	Minor

Table 11. Spain (Iberian Upwelling): Shellfish Aquaculture Risks

Identified climate-related risks in Shellfish Aquaculture - Iberian Upwelling					RCP4.5			RCP8.5			Overall Risk (all scenarios and timescales)
Category	Climate Change Drivers	Potential Impact	Modelled?	Stakeholder Consensus	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating
			Yes/No	Std. Dev	2020	2030	2050	2020	2030	2050	
Ecosystem	Harmful algal blooms	Harvesting closure	No	0.95	Severe	Severe	Severe	Severe	Severe	Severe	Severe
Ecosystem	Water temperature, solar radiation, wind regime and continental runoff	Lack of mussel seeds	Yes	1.20	Major	Major	Major	Major	Major	Major	Major
Ecosystem	Predators	Predators eat mussels seeds	No	1.27	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Ecosystem	Extreme weather events (strong storms)	Loss of rafts	No	1.37	Minor	Minor	Minor	Minor	Minor	Moderate	Moderate
Ecosystem	Extreme weather events (strong storms)	Detachments of mussels from the ropes	No	1.20	Minor	Minor	Minor	Minor	Minor	Moderate	Minor
Socio-economics	Extreme weather events (strong storms)	Increased production costs	Yes	1.43	Minor	Minor	Minor	Minor	Minor	Moderate	Minor
Socio-economics	Extreme weather events (strong storms)	Decreased production volume	Yes	1.34	Minor	Minor	Minor	Minor	Minor	Minor	Minor

Table 12. Spain (Iberian Upwelling): Shellfish Aquaculture Opportunities

Identified climate-related opportunities in Shellfish Aquaculture - Iberian Upwelling					RCP4.5			RCP8.5			Overall Risk (all scenarios and timescales)
Category	Climate Change Drivers	Potential Impact	Modelled?	Stakeholder Consensus	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating	Risk Rating
			Yes/No	Std. Dev	2020	2030	2050	2020	2030	2050	
Ecosystem	Water temperature, wind regimen and continental runoff	Mussels reach the commercial size faster according to the harvesting strategy	Yes	1.05	Major	Major	Transformative	Major	Major	Transformative	Major
Ecosystem	Wind regimen and continental runoff regimes	Increased food availability	Yes	0.79	Moderate	Moderate	Major	Major	Major	Transformative	Major
Socio-economics	Water temperature, wind regimen and continental runoff	Slight output increase	Yes	0.97	Minor	Minor	Minor	Minor	Minor	Minor	Minor

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