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**Implementing the Strategic Guidelines on EU Aquaculture
Climate-change Adaptation in the Aquaculture Sector**

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LIST OF ACRONYMS

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
CEN	European Committee for Standardisation
CINEA	European Climate, Infrastructure and Environment Executive Agency
CMS	Cardiomyopathic syndrome
DG MARE	Directorate-General for Maritime Affairs and Fisheries
EAF	Ecosystem Approach to Fisheries adopted by the FAO Committee on Fisheries (COFI)
DSS	Decision support software
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
EMFF	European Maritime and Fisheries 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	Feed 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 and the Black Sea
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
MCCIP	Marine Climate Change Impacts Partnership
MNSPA	Multiannual national strategic plan for aquaculture
MSP	Maritime spatial planning
OA	Ocean acidification
OT	Outcome target
PKD	Proliferative kidney disease
RAS	Recirculating aquaculture systems
SAIC	Scottish Aquaculture Innovation Centre
SGR	Specific growth rate
SME	Small and medium-sized enterprise
UNE	Spanish Standardisation Association

GLOSSARY

This glossary provides short definitions of the terms used in this document, taken from various sources, including the European Committee for Standardisation (CEN) Workshop Agreement and the Intergovernmental Panel on Climate Change (IPCC) 2022 Report (Annex II).

Term	Definition
Adaptive capacity	The 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 adjusting to actual or expected climate change and its effects. In this document, adaptation seeks to minimise or avoid harm, or exploit opportunities.
Climate Adaptation Plan (CAP)	Long-term strategic plan that aims to help a farm or national aquaculture industry to develop adaptation measures for climate change effects.
EFABAR	A voluntary code of good practice for responsible farm animal breeding developed under 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 likely climate-driven event.
Outcome Target (OT)	Specific and measurable performance goal, 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 document, risks can arise from the 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, investments, infrastructure, services (including ecosystem services), ecosystems and species.
Risks - short term	Risks that might occur within a few years.
Risks - long term	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. 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.

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1 INTRODUCTION

In May 2021, the European Commission adopted a *Communication on strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030*([1]) ('the Strategic Guidelines'). These guidelines set the vision for EU aquaculture to grow into an even more competitive and resilient sector and become a global reference for sustainability by 2030. They are the result of extensive consultation with EU Member State experts on aquaculture and the Aquaculture Advisory Council (AAC) as well as a public consultation.

The Strategic Guidelines cover all issues of relevance to the sustainable development of aquaculture in the EU and provide concrete recommendations and proposals for action to the Commission, Member States and the AAC. The Strategic Guidelines note that 'the aquaculture sector will need to adapt to the many disruptive impacts of climate change and improve its resilience'.

European Union (EU) food production systems, including aquaculture, are being challenged by changes in the climate resulting from global warming. This affects all forms of aquaculture, in both inland and coastal regions. Short-term impacts, such as extreme weather events, can destroy production infrastructure and limit the amount of water available to farmed species. Diseases, parasites, predators (including invasive non-indigenous species) and algal or jellyfish blooms can also decrease production. Longer-term impacts associated with changes in water temperature, salinity, ocean acidification (OA), 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 production to encompass new species or to achieve faster growth of existing ones.

As indicated in the Strategic Guidelines, the EU's climate adaptation strategy and national strategies/plans provide a framework for policymakers to ensure that the climate-change adaptation measures they implement are comprehensive and efficient. The 2021 EU climate adaptation strategy ([2]) sets out how the 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 as to step up international action on climate change adaptation. The European Green Deal ([3]) and the farm to fork strategy ([4]) both underline the importance of climate adaptation for the transition to robust and resilient EU food systems.

The Strategic Guidelines call for specific sectoral adaptation strategies to address the aquaculture sector.

Annex I, Section 2.1.4, calls for the Commission to 'Develop a guidance document on sectoral climate adaptation plans and strategies. Member States are encouraged to support the development of sector-specific national, regional, transnational, or sea-basin climate adaptation plans (CAPs), consistent with national adaptation strategies and plans, as well as the corresponding European Committee for Standardisation (CEN) standard for the development

([1]) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030 (COM/2021/236 final) (Aquaculture guidelines (europa.eu)).

([2]) 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

([3]) Communication on The European Green Deal | European Commission (europa.eu).

([4]) Farm to Fork Strategy - European Commission (europa.eu).

of CAPs. The European Commission's Guidelines on Member States' adaptation strategies and plans ([5]) could also be a reference for the development of a CAP.

This staff working document develops and provides further details on the key recommendations outlined in the Strategic Guidelines to address the impact of climate change on the aquaculture sector. Annex II describes the methodology used to prepare it.

Its principal objective is to support authorities and policymakers in Member States and the aquaculture sector in creating and updating CAPs for aquaculture. To that end, it presents the effects (both negative and positive) that climate change can have on EU aquaculture. It also describes a detailed process for developing a CAP and provides examples of good practices for several climate adaptation measures. Finally, it details some of the existing knowledge gaps and policy recommendations to adapt to climate change.

Taking into consideration the continuous innovation and technological development in the aquaculture sector, the information provided in this staff working document will be updated in the future to match progress in these areas. The Commission will provide these updates on the EU Aquaculture Assistance Mechanism website ([6]).

Note that the hyperlinks in this document are valid at the time of publication. Should updates to these hyperlinks be necessary in the future, they will be provided on the EU Aquaculture Assistance Mechanism website.

Note also that this document does not cover climate mitigation (reduction of emission of greenhouse gases of aquaculture). The energy transition of the EU aquaculture sector is covered in a separate document ([7]).

Climate adaptation has multiple cross-cutting elements that include environmental management, husbandry and animal welfare-related practices and regulatory issues such as access to space and water. These are covered by other documents on the regulatory and administrative framework for aquaculture ([8]), planning of space and access to water for marine aquaculture ([9]), access to space and water for freshwater and land-based aquaculture ([10]), good animal husbandry ([11]) and future documents on environmental performance and fish welfare.

2 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 the two main types of production systems: land-based and marine production systems.

Climate effects are also related to geographical areas. Reports (including those by the IPCC ([12]) and EEA ([13]) show areas and sea basins in Europe that are more susceptible to certain types of

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([5]) 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)
([6]) aquaculture.ec.europa.eu
([7]) SWD (2024) 280- Implementing the Strategic Guidelines on EU Aquaculture. Energy transition in the EU aquaculture sector
([8]) Regulatory and administrative framework for aquaculture | EU Aquaculture Assistance Mechanism (europa.eu)
([9]) Planning of space and access to water for marine aquaculture | EU Aquaculture Assistance Mechanism (europa.eu).
([10]) SWD (2024) 281- Implementing the Strategic Guidelines on EU Aquaculture. Access to space and water for freshwater and land-based aquaculture
([11]) Document on good husbandry practices Good husbandry practices | EU Aquaculture Assistance Mechanism.
([12]) https://www.ipcc.ch/
([13]) EEA briefing 'How climate change impacts marine life', including an exploratory approach to mapping the *European Marine Climate Change Index* (EMCCI) for Europe's seas http://www.eea.europa.eu/publications/how-climate-change-impacts

climate effects. These are known as 'hotspots'. Climate stressors and climate effects vary considerably across regions (of Europe), but also between regions and even local areas within a particular country. CAPs should consider the variability of climate change effects within a country, and adaptation measures should be tailored to the specific situation of each region and the type of aquaculture production it features.

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. However, there are regional examples that show that these climate change effects have long begun, with numerous impacts already affecting production to different extents.

The EEA EU Climate Risk Assessment (EUCRA) report ([14]) also identifies risks for the food sector, including on aquaculture and indicates the need for adaptation measures.

The below table provides an overview of the climate risks on EU aquaculture, by production environment and classified as moderate, major, severe or not applicable. Severe risks would need immediate adaptation actions. Recirculating aquaculture systems (RAS) are not included, as they are generally considered to be removed from climate and environmental risks.

Table 1. Overview of climate risks on EU aquaculture, by production environment

This assessment of climate risks by production environment is based on short and long-term scenarios derived from several EU projects and other references. The climate change drivers/effects are adapted from the CLIMEFISH project. Risk is assessed as being moderate, major, severe or not applicable (n/a).

Risk	Marine environment		Land-based environment		
	Far from shore	coastal	Lagoons & wetlands	rivers	ponds
Increased temperature - mortality due to biotic stress (incl. oxygen, salinity)	Moderate	Major	Severe	Major	Moderate
Increased temperature – evaporation losses	n/a	n/a	Moderate	Moderate	Major
Increased temperature - plankton/jellyfish blooms	Moderate	Major	Major	Moderate	Major
Increased temperature - higher presence of harmful pathogens	Moderate	Severe	Moderate	Major	Major
Increased temperature - higher presence of predators	Moderate	Moderate	Moderate	Moderate	Moderate
Increased temperature - Decreased water availability	n/a	n/a	Moderate	Major	Moderate

([14]) https://www.eea.europa.eu/publications/european-climate-risk-assessment

Extreme weather – Infrastructure losses, sea level rise and/or escapes	Moderate	Moderate	Moderate	Moderate	Moderate
Extreme weather – coastal erosion	n/a	Major	Major	n/a	n/a
Extreme weather - flooding	n/a	n/a	Moderate	Major	Moderate

Further details on these risks per production environment and system are provided below.

2.1 Land-based production systems

For simplicity purposes, this document splits land-based production systems into pond systems and wetlands, lagoons, flow-through/raceways and recirculating aquaculture systems (RAS).

2.1.1 Pond systems and wetlands

Fishponds are artificial constructions that maintain significant (more than 300 000 ha) artificial wetland habitats 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 located 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 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, which 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 ([15]).

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, pike, etc.) of the same age class. In the EU it is mostly an extensive (or semi-intensive) farming production system that uses natural food sources (mainly zooplankton), often complemented with cereals.

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

The case study in the EU-funded CLIMEFISH project 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*.

([15]) Palásti et al., 2020.

- 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 on whether and to what extent it is negative. For example, higher phytoplankton production might result in more food for fish, but it may also lead to more eutrophic situations, with high oxygen levels during the day and low oxygen levels during the night. There is also the risk of algal blooms, including toxic (blue) algae.

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

- Sub-optimal 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.

Producer organisations from Czechia and Hungary consider that the greatest risks for pond aquaculture in the short term are severe weather events, availability of water, the increase of the feed conversion ratio (FCR) and an increased number of predators. In the *longer term* they identified extreme water events and water availability as the highest risks. Emerging cyprinid viruses were identified as both short- and long-term risks for the aquaculture sector.

2.1.2 Lagoons

Coastal lagoons are mostly 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 artificial enclosures capture fish migrating with the natural lagoon currents of the Adriatic coast. Lagoon or coastal wetland production of fish and crustaceans is practised 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 biodiversity - coupled with their status as buffer zones between the sea and 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 are 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.

The Marine Climate Change Impacts Partnership (MCCIP) report published in 2018 provides an overview and management options for saline lagoons across the UK ([16]). According to this overview, the biggest climate change threats to saline lagoons are relative sea level rise, changes in seasonal temperature, storminess and rainfall patterns.

([16])https://www.mccip.org.uk/sites/default/files/2021-07/mccip-saline-lagoons-report-card_second-run_v3.pdf

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.

2.1.3 Flow-through/raceways

Flow-through and raceway systems take water from rivers or wells and are associated with the traditional culture of rainbow trout in many European countries. Other species cultured in these systems are other trout species and sturgeon. 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 not even have access to water due to drought restriction provisions. When floods occur, water quality degrades abruptly (due to various factors, including suspended solids, debris carried by flood waters and other organic materials that may result from the poorer efficiency of urban wastewater treatment during extreme precipitation events), 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 rainbow trout production underlined, most production units are managed by small and medium-size enterprises (SMEs) (and some micro-enterprises) 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 rainbow trout production in Denmark, Germany, Türkiye and the UK for 2050 showed that the economic effects of climate change could differ depending on the number of days of optimum growth per year and on 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 highest in the UK, followed by Denmark, then Germany, and is lowest in Türkiye. They also noted the strong link between temperature and disease, highlighting that proliferative kidney disease (PKD) could be a problem with future temperature scenarios in all the reference countries, and especially in Türkiye.

Producer organisations and/or associations 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 a higher number of predators. Emerging pathologies, plus a rise in existing ones, were also selected as a high risk in the short term. In the longer term, the key risks identified by these organisations were water availability and a decrease in production volume.

2.1.4 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 all 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.

The effects of climate change are therefore considered to have minimal impact on RAS systems operating indoors, as high levels of control can be applied.

2.2 Marine production systems

For simplicity purposes, this document splits marine production systems into floating net pen systems for finfish, and inter-tidal or suspended culture for bivalve molluscs (from the surface or off-bottom) and seaweeds.

2.2.1 Net pen systems

Floating net pen systems, in units of several net pens moored together and anchored to the sea floor, are used to produce cold and warm water fish species. The net pen units are supplied by air-blown automatic feeding systems. They rely on boats for their servicing and operations.

Climate effects on these systems are multiple and present both risks and opportunities for producers. These effects not only relate to changes in the water physico-chemistry, but also include storm events, sea level rise, changes in the impacts of harmful algal blooms (HABs), jellyfish blooms, and increase in parasites, predators and diseases.

For example, the EU-funded iFishIENCi project ([17]) (Deliverable 4.3) suggested that increasing winter sea temperatures (*in the short and long term*) may be beneficial for the 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 when there is more chance of higher temperatures combined with lower oxygen concentrations, which increases 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 line with demand.

The conclusions of a 2021 study of climate scenarios and potential effects on marine aquaculture in Greece ([18]) were even more alarming. Studying predictive models for biomass production and profitability under a production scenario for 200 000 individuals, at 800g market size, this study simulated three extreme event scenarios, namely:

‘Mild extreme events’ (1% mortality for heatwaves and storms).

‘Intense heatwaves’ (5% and 1% mortality for heatwaves and storms, respectively).

‘Intense storminess’ (1% and 5% mortality for heatwaves and storms, respectively).

([17]) 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

([18]) Stavrakidis-Zachou et al. (2021).

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 *in the mid-term* (2030) but will double in *the long-term* (2050) projections. Initially, the production volume will show marginal losses of around 0-16% leading to moderate profit losses of 1-25%. However, the authors suggested that by 2050 biomass production and profit will drastically deteriorate across all scenarios. The decrease in biomass will generally be around 25-40%, which will have devastating effects on farm profitability. These results are attributed to the increased frequency of extreme events *in the long term*, and predominantly to heatwaves. The authors concluded that while the other considered factors may partially compensate 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 varying potential impacts on the sector. Greek stakeholders participating in this case study identified the following key risks for all climate scenarios and time periods:

Inhibition of growth and increase in mortality. This was considered a major risk in the biological category for both climate scenarios and time periods. It relates to the decrease in oxygen solubility in water at higher temperatures, which in turn decreases oxygen in water. With insufficient oxygen, the appetite, growth and survival rate of fish decreases.

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

Increases in both HABs and fouling of the net pens. From the ecological and environmental category, these were the principle risks identified.

Increased presence of pathogens. This impact received the highest risk rating and was considered a severe negative impact by both stakeholders and scientists for all climate scenarios and time periods.

All other impacts were considered to be moderate, such as the impact on the suitability of farm sites, water quality deterioration, risk for anoxic conditions, increased size variability, infrastructure damages, increased use of antibiotics and an increase in escapees.

A more recent publication provides insight into the real-world complexities ([19]). Atlantic salmon (*Salmo salar*) production in Norway was used as a case study to illustrate the need to consider the impacts of 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 the one presented in the publication, can be used by the aquaculture industry, researchers and policymakers as a foundation for more targeted and

([19]) Falconner et al., 2022.

detailed climate change impact analysis, risk assessment and adaptation planning. The excel file annexed to the publication can serve as a template for other regions and other species.

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 them. However, water temperature and husbandry effects (e.g. increased fouling, higher FCR) were not generally considered as major risks in the short term.

2.2.2 Inter-tidal and suspended systems

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

Bivalve molluscs account for more than 50% of aquaculture activity in the EU and there are many different and interlinked issues that have a direct impact on the production environment as a result of climate change, including increasing pH and salinity and various abiotic and biotic factors.

As shown by the significant mortality caused since 2008 by a genotype of the OsHV-1 virus, bivalve molluscs are vulnerable to climate changes that lead to the emergence of new pathogens. However, bivalve mollusc appear to have some capacity to adapt to climate change, with tolerance and/or resilience to environmental stressors and genetic adaptation to their changing habitats ([20]).

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 due to a recent cyclical reduction in natural spatfall, but also to increased predation of settled spat.
- Loss of rafts: Infrastructure losses due to storm activity.
- Detachment of mussels: Also from storm effects.

The producer organisation in Galicia (Spain) confirmed the risks listed above. They indicated that water temperature is the highest short-term risk, with HABs 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 key 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 (seaweed). Currently, there is no extensive information on the impacts of climate change effects on EU algal production. However, more knowledge should be forthcoming as a result of the implementation of the EU Algae initiative and its EU4Algae platform ([21]).

([20]) Byrne et al., 2020.
([21]) https://maritime-forum.ec.europa.eu/en/frontpage/1727.

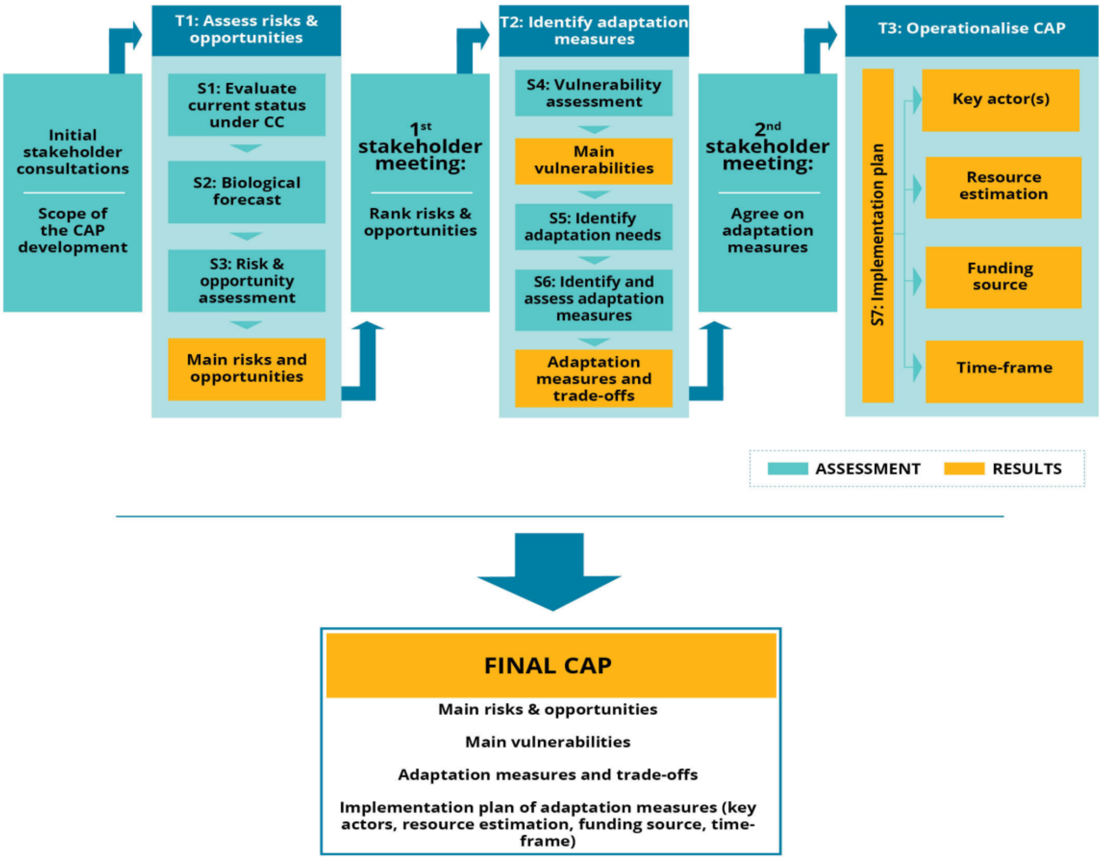
3 CREATING CLIMATE ADAPTATION PLANS FOR AQUACULTURE

The purpose of this section is to support Member States in developing a climate adaptation plan (CAP) for aquaculture. It is based on multiple information sources, but principally on a voluntary European standard to develop tailor-made CAPs, published by the European Committee for Standardisation (CEN) as a Workshop Agreement ([22]). Other key sources include the CLIMEFISH Deliverables 4.3 and 6.2 and a related scientific publication ([23]).

The CEN Workshop Agreement is a consensus-built, repeatable step-by-step methodology to develop a CAP. It is presented as a draft standard and may also be used as the basis for creating a high-level standard (e.g. ISO).

The CAP development process (Figure 1) serves to identify 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 includes identified risks and opportunities, identified vulnerabilities, identified adaptation measures and an implementation plan.

Figure 1. Overview of the CAP development process



Source: CEN Workshop Agreement. CWA 17518:2020

([22]) CWA 17518:2020.
([23]) Pham et al., 2021.

The CAP may be linked to the national (climate) adaptation plan or linked or incorporated into the multiannual national strategic plans for aquaculture. It could also form the basis of a multi-stakeholder strategy and action plan.

3.1 Stakeholder participation

Stakeholder involvement is fundamental when developing a CAP. According to the CEN Workshop Agreement, stakeholders must be made aware of and invited to open meetings, and the process should include a feedback period for each of the steps to encourage participation and ensure transparency.

The Fisheries and Aquaculture Monitoring, Evaluation and Local Support Network (FAMENET) as well as fisheries local action groups (FLAGS) are effective means of mobilising local groups. Financial support for community-led local development is provided under the European Maritime, Fisheries and Aquaculture Fund (EMFAF).

A diverse stakeholder community can help identify relevant climate effects and provide examples of good adaptation measures. Several techniques can be used to select stakeholders, but to ensure that all the sustainability pillars are represented, the stakeholder typology shown in the table below (adjusted for the purposes of this document) should be applied.

Table 2. Stakeholder typology

STAKEHOLDER TYPE	STAKEHOLDERS
Producers: Those using space, placing infrastructure, or taking resources from the marine or inland production system.	**Primary operators (aquaculture producers):** Operators who provide the raw material for processing. In this case, aquaculture operators (producers) and/or aquaculture producer associations.
Beneficiaries: Those benefiting from the ecosystem services and goods created by the production system and delivered by the producers.	**Secondary operators (processors):** Operators that receive the raw material e.g. processing companies and others that sell and/or market the products.
Affected: Those affected by the producers, those affected by the producers and the policy decisions, or those impacted by the decisions.	**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 policymaking 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 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 and infrastructure.

Source: 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, so as to provide sufficient resources to develop the work. This can be enshrined in a CAP Agreement, signed by all stakeholders participating in the process to signal their commitment to the work to be done.

3.2 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 an aquaculture production system. This implies that the system should be broken down into its core components. Annex B of the CEN Workshop Agreement provides a sample template.

Impacts should be evaluated as resulting in risks or opportunities. As there are several methods for assessing risks and opportunities, it is necessary to identify the most appropriate one for each case considering, for example, data availability and the nature of the production system. FAO's online EAF (Ecosystem approach to fisheries) toolbox ([24]) provides an overview of the various risk assessment methods, including selection criteria. Although it has been designed for fisheries, it is also applicable to aquaculture.

The assessment involves 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 carried out 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 3). This is often achieved by measuring 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.

Table 3. Assessment of risks and opportunities

Category /Risk level of impact	Risk description	Category/ Opportunity level	Opportunity description
No	Acceptable, not a risk.	No	Irrelevant: not an opportunity.
Minor	Acceptable: no specific control measure needed.	Minor	Limited opportunity: minor improvement to current conditions.
Moderate	Maximum acceptable level: management measure required in medium to long term.	Moderate	Potential opportunity for improvements: to be considered under special circumstances.

([24]) www.fao.org/fishery/eaf-net/toolbox

Category /Risk level of impact	Risk description
Major	Not desirable: Increase management actions or implement further risk control in the near future.
Severe	Unacceptable: Major changes required to management in the immediate future.

Category/ Opportunity level	Opportunity description
Major	Significant improvements to present conditions: actions should be considered in the near 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 to expected climate change impacts.

Adaptation measures can be built directly based on this assessment.

3.3 Identification of adaptation measures

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

Table 4. Examples of indicators and outcome targets for the identification of adaptation measures

Indicators	OT
Specific growth rate (SGR) and on-growing period at the 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 (per year) where husbandry operation procedures are inhibited due to limited infrastructure durability to extreme weather	Number of non-operational days ≤ X days
Feeding costs where relevant (€ / tonne of fish produced)	€ / tonne of fish produced

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. Outcome targets (OTs) and indicators are applied directly to the production process to evaluate success.

2. Policy recommendations: Adaptation measures are targeted to the industry but require prior legislative change or policy recommendations from local, regional, national or EU authorities in order to increase the resilience of the sector. Examples include more

flexible legislation, the development of financial instruments to facilitate the implementation of adaptation measures, or a facilitated insurance scheme. No OTs or indicators are required for this category.

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

The EU Bioeconomy Monitoring System indicator update ([25]) includes 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 aquaculture in net pens, 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.

3.4 Implementation

It is imperative that stakeholders participating in all previous steps have some level of involvement in the implementation of the CAP. The level of detail when describing the key actors in the CAP is up to the CAP consortium, i.e. whether it will include 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 or engineers).

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

In addition, the expected time frame for implementing 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.

Member States are encouraged to integrate the CAP into their MNSPA or national (climate) adaptation plan, or into any future updates of these documents.

3.5 Monitoring and evaluation

Monitoring and evaluating the implementation of the adaptation measures not only provides information on the efficiency and progress of the measure but also makes it possible to identify unexpected barriers that may require additional action or improvements.

Monitoring indicators can also help with collecting data and evaluating climate change-related actions carried out by Member States.

Monitoring can be internal and/or external. Internal monitoring is generally carried out 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.

3.6 Updating

Climate effects are happening now. They may be relatively constant or they may rapidly accelerate in the short and medium term. However, contributions to current knowledge on these

([25]) JRC Publications Repository - EU Bioeconomy Monitoring System indicator update (europa.eu).

effects and the development of technology to adapt to them take time. Therefore, CAPs must be updated periodically through new rounds of consultations.

It is recommended that the CAPs be prepared or updated before the next MNSPA or national (climate) adaptation plan. A stakeholder-driven approach is also recommended to provide more detail on the specific priorities, adaptation measures and supporting policies or financial instruments.

One example for reference is the 'Guidance Document for Climate Change Adaptation of the Spanish Aquaculture Sector ([26])', by the Spanish Fundación Biodiversidad, which is aligned with the Spanish multiannual strategic plan.

4 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, each of which address a specific climate adaptation measure (see Table 5 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. An indication of 'market readiness' is included, where project, prototype or (commercially available) product status is indicated, or a new classification has been proposed, or where guidelines or standards have already been enacted or put in place.

Table 5. Overview of good practices on climate adaptation measures

ADAPTATION MEASURE	GOOD PRACTICE	COUNTRY	MARKET READINESS
Practical impact forecasting and decision-making tools	Artificial intelligence (AI) to automate the process of identifying HAB and to provide an early warning system.	UK	Project/Prototype
	AI-based phytoplankton identification.	Ireland	Prototype
	Automated data integration to existing systems to provide prediction measures for fish health & disease outbreaks.	Norway	Product
	Provision of data on various environmental risks.	Italy	Product
	Automated collection of data from mussel farms for monitoring authorities.	Denmark	Project
	Forecasting risks of key viruses for carp production.	Poland	Project/new classification

([26])Guidance document for climate adaptation of the Spanish aquaculture sector: https://www.observatorio-acuicultura.es/sites/default/files/images/adjuntos/libros/guia_para_la_adaptacion_del_sector_acuicola_espanol_a_los_riesgos_derivados_del_cambio_climatico.pdf

ADAPTATION MEASURE	GOOD PRACTICE	COUNTRY	MARKET READINESS
Selective breeding for increased resilience	Key selection traits to assess if current strains are sufficiently tolerant to short-term climate changes and/or disease threats.	No sufficient application	Not applicable
Production opportunities and diversification	Diversification of species.	Croatia and Malta	Enacted
	New trout strains.	Germany	Enacted
	Production of tilapia and shrimp.	EU ([27])	Prototype
	Turning toxic algae blooms into business opportunities.	Lithuania	Prototype
	Combined culture of seaweed and bivalve molluscs.	Denmark	Project
	'Aquaculture readiness level' – for species diversification.	Norway	New classification
	Technical screening criteria for escapes from net pens.	UK	New standard
Infrastructure and system development	Technical standard for marine finfish net pens and equipment.	Spain	New standard
	Management of fish escapes.	Spain	Project
	Spring-based moorings to reduce load and fatigue.	Ireland	Product
	Underwater vehicles for continuous automated net cleaning.	Norway	Product
	System development in inland (pond) systems.	EU	Product
	Annual risk analysis for specific farms and biosecurity analysis for farming locations.	Croatia	Enacted
	Monitoring and decision support tool.	Greece	Prototype
	Oxygen sensors for lagoon-based bivalve mollusc culture. Cooling systems in bivalve molluscs finishing ponds.	France	Product (oxygen sensors) Prototype (cooling systems)
	Aquaculture Network to provide advice to SMEs on a case-by-case basis in the management of water use.	Germany	Enacted

([27]) Where EU is referred to in this table, it means either various EU Member States or an EU-wide practice.

ADAPTATION MEASURE	GOOD PRACTICE	COUNTRY	MARKET READINESS
	New combined pond farming techniques.	EU	Prototype
	Submersible bivalve mollusc production structures.	Denmark	Prototype
	Using expert advice for relocation of farms/disease prevention plan.	Slovenia	Enacted
Location planning and relocation	Urban farming: aquaponics systems to avoid climate effects and produce fresh vegetables locally.	Czechia, Belgium and Germany	New production systems
	A 'suitability index' for site location in estuaries for bivalve mollusc production.	Portugal	New classification of suitability areas
	Decision support software to simulate climate effects on farm economics.	Greece	Prototype
Management of the introduction of non-native species	Technical guidelines of the FAO General Fisheries Commission for the Mediterranean and the Black Sea (GFCM), including good practices on quarantine measures and monitoring programmes.	FAO/GFCM	Not applicable

Aquaculture feeds 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.

4.1 Practical impact forecasting and decision-making tools

Background/Challenges

As explained above, climate change effects can make the environment in which aquaculture production takes place subject to increasingly rapid changes with potentially substantial impacts. These include storm and localised extreme weather events and blooms or swarms of algae, parasites and jellyfish that can quickly create health and welfare problems for aquaculture stocks, and/or food safety issues for bivalve mollusc production. Technology and data integration provide excellent prospects for better real-time and 'holistic' environmental monitoring and forecasting, as well as improved production infrastructure.

Both technology and data integration should be prioritised for rapid development and deployment. Data integration is extremely important to individual operators. It can also increase the accuracy of national monitoring by identifying climate change monitoring indicators and including them in Member States' data collection. The EU has proposed indicators for climate adaptation, for example in the update of the Bioeconomy Monitoring System indicator.

Member States are encouraged to select the most suitable indicators that can be used to monitor their CAPs, in order to measure progress in their implementation.

While mapping exists for HABs – 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 a new phenomenon that 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 warning systems (i.e. a mobile app or alert), aquaculture operators can take measures to avoid mortality and/or, in the case of bivalve molluscs, to avoid potential food safety risks. These measures 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 net pen ring, providing a potential barrier to ‘undesirable’ organisms (sea lice, jellyfish) in the water column.

In addition, several satellite-based tools are available for detection and forecasting. Three examples of tools developed with EU funds are:

S-3 EUROHAB ([28]) which uses data from the European satellite Copernicus Sentinel 3 to detect eutrophication and harmful algal bloom (HAB) events in the French-English Channel. S-3 EUROHAB has developed a web-based HAB 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 bivalve mollusc end-users.

The **PRIMROSE** ([29]) (Predicting the impact of regional scale events on the aquaculture sector) project has created a web portal that makes various indicators available, including HABs. It has built on the work of the predecessor project, ASIMUTH, by improving the accuracy of forecasts (with a traffic light system), increasing the regional coverage

([28]) Interreg France (Channel Manch) England project S-3 EUROHAB: https://s3eurohab.eu/

([29]) Interreg Atlantic PRIMROSE project – web portal: https://primrose.eofrom.space/

(improved spatial resolution provided by new generation EO Sentinel satellite data) and increasing the number of controlled parameters.

The **SEASTAR** project ([30]) 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, monitor and record rapid changes in physical variables (i.e. temperature, oxygen and salinity) that may be related to extreme weather events. The project is being piloted in the Gulf of Follonica (Tuscany, Italy) with the collaboration of nine producers (eight fish farmers and one bivalve mollusc farmer). The reference area is an allocated zone for aquaculture (AZA) that will be nested with sensors. The sensor data will be validated with satellite data and in-situ data and made available to producers as dedicated software.

Examples of good practices in EU Member States and other countries

Good practice in forecasting and decision support tools relates not only to the tools themselves, but also to the way in which the data is presented, standardised and shared (simple traffic light systems), the accuracy and extent of forecast (number of days) 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) ([31]) 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 ([32]) 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 measures.

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

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

In **Italy**, the integration of satellite data with in-situ water samples and mathematical models provides tools to effectively manage environmental risks that can impair fish farm productivity. Water quality changes, storm activity and early warning of HABs can be predicted and, depending on the location, users have a 5–7-day window to implement contingency measures before a farming site may be compromised.

([30]) EMFF SEASTAR project: https://www.seastar-project.eu/

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

([32]) www.habreports.org

4.1 Practical impact forecasting and decision-making tools

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

In **Poland** ([33]), 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 the long term (to the end of the century). These 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 integrated 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.

4.2 Selective breeding for increased resilience to climate change

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 related to production (faster growth, better fillet yield) and (existing) disease resistance. Several national programmes are also selecting fish for better assimilation of feeds with novel (non-fish meal/oil) ingredients.

However, specific climate resilience to environmental effects, especially increased summer water temperatures, are not generally present in current breeding programmes and, in many cases, the current strains are not considered sufficiently tolerant to climate-related changes. It is therefore necessary to factor these into the current breeding programme management ([34]).

The information in the examples below was obtained from several experts in breeding. There is no good practice *per se* for breeding for resilience to climate-related changes, but the expert opinion is that not one of the key species below is sufficiently resilient to climate change effects.

In Finland, rainbow trout are selected for growth, maturity age, body shape, survival, carcass, resistance against parasites and to avoid skeletal deformations. However, the current strains are not considered to be sufficiently tolerant to short-term climate changes/disease threats, as water temperatures are often above the tolerance level of rainbow trout. This has negative impacts on broodstock fish, eggs, fingerlings and on-growing fish, i.e. on all life stages. There are also diseases that are temperature dependent (e.g. *Flavobacterium columnare, Saprolegnia fungus*) that have drastic negative effects on the industry. Finally, there may be diseases that spread northwards due to increased temperatures.

([33]) Panicz et al., 2022.

([34]) Most breeding programmes operating in Europe are linked to the European Forum of Farm Animal Breeders (EFFAB) and to its code of good practices for selective breeding (Code EFABAR) which is reviewed/updated every 3 years. These good practices are used as the 'minimum requirement' for the breeding programmes mentioned here. See Code EFABAR: https://www.effab.info/modern-animal-breeding/responsible-breeding/code-efabar/

4.2 Selective breeding for increased resilience to climate change

In France, rainbow trout are selected to improve growth to portion (300 g) or large size (2-3 kg), carcass, fillet, and trimming yields, disease resistance, female reproductive performance and farming practices (stocking density, fish meal/oil substitution in feeds, 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.

Measures to support climate adaptation through selective breeding include:

- management and conservation of genetic resources through the French aquaculture cryobank CRYOAQUA;
- indirect selection to improve feed efficiency (and having fish less demanding in oxygen), with gains of 20% in 10 generations in rainbow trout and 20% in six generations in sea bass;
- a national reference laboratory and platform for selection to improve disease resistance in the main farmed species;
- research into the genetic basis for selection against hypoxia, hyperthermia, and cardio-respiratory capacity on diploid and triploid rainbow trout.

These improvements are providing genotypes with higher feed efficiency (see below) and are less demanding in oxygen in summer. However, breeding programmes should still scope to adapt better to climate change.

In Ireland, the breeding programme for Atlantic salmon is currently focused on cardiomyopathic syndrome (CMS), growth, late sexual maturity and pigment. Only one strain farmed in Ireland is recognised as being fairly robust for future climate effects, but no strain is completely tolerant to disease or higher temperatures. 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 the 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.

The current strains of bass and bream are not sufficiently tolerant to short-term climate changes/disease threats. The fish typically survive temperature highs, but they 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.

The main objectives of a specific programme for the breeding of bivalve molluscs to build resilience to climate change impact (**SHELLFISHBOOST**) ([35]) include developing/optimising advanced tools for genetic selection (molecular tools, optimised breeding schemes) and estimating genetic parameters for key traits (growth, resistance to heatwaves, salinity stress, summer mortalities and presence of harmful algal toxins).

[35] https://www.bluepartnership.eu/projects/boosting-resilience-european-shellfish-production-against-climate-change-related.

4.3 Production opportunities and diversification

Background

Opportunities provided by climate change effects include:

- improved winter growth;
- reduction of the duration of the overall life cycle (egg to harvest);
- potential production of larger individuals at market size (for example sea bass);
- increased primary production for pond aquaculture;
- increased algal production for faster bivalve mollusc growth;
- production of existing species in new areas/zones;
- production of new species in existing or new areas/zones.

Farming in new areas and sites that are better suited to production, or using existing AZAs for producing species that are more resilient or tolerant to climate effects in that zone, could help expand and/or diversify overall (EU) aquaculture production.

The EU project DIVERSIFY ([36]) (which ran 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 cephalus*) 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.

However, diversification towards new species is not straightforward. Each candidate species should be studied and its ‘readiness for aquaculture’ and potential risks of introduction (for non-indigenous species) should be assessed and all trade-offs considered.

Proposed solutions/Adaptation measures

The CLIMEFISH and CERES case studies revealed that **increasing water temperatures** can also present opportunities for farms. They highlighted 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.
- Decrease in feed costs due to change in feed conversion rates.

For seabass/sea bream farming in Greece:

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

For bivalve mollusc (mussel) farming in Spain:

(36) http://www.diversifyfish.eu/summary.html

4.3 Production opportunities and diversification

- Faster growth related to increased availability of phytoplankton in the water column.

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 them can be used as templates for the development work of a CAP.

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 common features of farming.

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

Examples of good practices in EU Member States and other countries

In its Deliverable 4.2, CERES cites the example of farming different species or strains of trout to overcome environmental changes, for example, the '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.

Led by the Nature Research Centre in Lithuania, the EU-funded project **AlgaeService** ([37]) 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 them 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. The project, which ended in November 2023, will produce a business plan for macro-algae and cyanobacteria.

In **Denmark**, focus is being placed on 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. While not yet used in commercial cultures, this combined culture is a mitigation measure (rather than a climate adaptation measure) that can reduce the otherwise negative effects of climate change and be beneficial for the growth of both species.

A study ([38]) has proposed the concept of **'aquaculture readiness level'** in Norway to assess whether the farming of a range of existing and potential species will be successful. The study considered about 50 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 assessment tool in other countries and regions.

([37]) AlgaeService: https://algaeservice.gamtostyrimai.lt/

([38]) Falconer et al., 2024.

4.4 Infrastructure and system development

Background/Challenges

Many of the expected climate effects will have a short duration and short-term effects, such as more frequent and intense storms, while others that are already under way will become considerably more significant, such as changes in water temperature, water chemistry, fouling, etc. There is a need for strengthening equipment, improving the (husbandry) management of the site, and net cleaning/fouling removal to address these challenges,

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. Reducing the total water volume can be achieved with partial or full recirculating aquaculture systems (RAS).

In marine systems, new net pen 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

Member States and industry organisations highlight new equipment standards as one of their climate adaptation measures. The development of stronger, more resilient equipment, using new materials and fibres, is an ongoing process, driven by research and developed by the equipment manufacturers. It is clear that new (or updated) equipment standards are effective climate adaptation tools that can have a 'whole sector' impact. New technical standards are either initiated as self-regulation by producer organisations, or as government regulations.

New technologies for net inspection and cleaning

Net inspections (for damage, holes, etc.) have generally been carried out by divers, either on a routine basis, or when damage has already been done. With increasing pressure on net pen 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 net pens and therefore improve fish welfare. For many years, research has focused on the development of anti-fouling products, although none are routinely used at present. Instead, nets are cleaned manually, which involves lifting a part of the net above water and cleaning it with high pressure water. Nets can also be cleaned with various equipment such as drum/disk/robotic 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.), as well as equipment inspection and testing (routinely and especially after storm events). The monitoring should be linked to action plans to remediate the risks. 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. These systems can increase the survival of early life stages that are most vulnerable to climate-induced effects and predation. They can also culture other species under intensive conditions in the extensive pond system.

Recirculation aquaculture systems (RAS)

As mentioned in Section 2, RAS are water-efficient and highly productive systems**,** generally removed from adverse environmental impacts, as they are 'closed' systems.

The move towards RAS is seen as a 'climate-proof' step and innovation is rapidly decreasing its cost and increasing its energy-efficiency. The percentage of EU production using RAS systems is therefore expected to increase significantly over the next decade.

(Offshore) marine closed and semi-closed containment systems are being developed and tested at an industrial scale in several countries. In Norway, the CtrlAQUA initiative ([39]) significantly furthered knowledge and innovation for setting up closed-containment systems in strategic parts of the Atlantic salmon production cycle. These systems may strongly reduce challenges related to lice, escapees and fish losses, and provide a controlled and safe production environment that is far less susceptible to the effects of climate change.

However, innovation is needed to bring closed-containment systems to a level that can enable a predictable production of Atlantic salmon. Necessary improvements include better reliability and cost-efficiency than traditional net pen culture and improving the robustness of fish (physiological and health/welfare) in these systems.

Examples of good practices in EU Member States and other countries

New equipment standards for adaptation to extreme weather and risk of escapes

In 2015, the **Scottish** government published a technical standard for Scottish finfish aquaculture ([40]) 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 2013 Aquaculture and Fisheries (Scotland) Act, 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. The annexes to the Act provide guidance on site operating procedures, and templates for developing the standard.

In 2019, **Spain** developed a technical standard for marine finfish cages and equipment (particularly to prevent storm damage). The standard was elaborated by UNE, the Spanish Standardisation Association, under its Technical Committee 173 on aquaculture processes and products (Standard name: UNE. Marine aquaculture, Marine fish farms: design and operation. UNE 173202) ([41]). To develop the standard, similar ones were analysed, for

([39]) https://ctrlaqua.no/innovation/

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

([41]) UNE 173202:2019: https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0062824 example ISO 16488: Marine fish farms-Open net cage-Design and operation. The standard was financed by the Spanish Ministry for Agriculture, Fishing and Food. Its implementation is voluntary but needs to be certified by a third party. After storm Gloria caused severe damage to cage farms in Valencia and Murcia, the 'Gloria' project ([42]) was launched in 2020 to advance knowledge on and the management of fish escapes from aquaculture facilities due to extreme events and thereby reduce losses and improve the sector's resilience to the effects of climate change. The Gloria project was renewed in 2022 ([43]).

While not a new standard, to protect against extreme weather events, a company based in **Ireland** is proposing a system of springs designed for use in long-term mooring applications such as cage aquaculture. 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. As the springs absorb energy, the plan is to develop the system so that this energy can be harnessed and used for other systems in the cages.

New technologies for net inspection and cleaning

Several technology companies in **Norway** are developing AUVs that run autonomously to keep nets clean. One such company is making partial use of 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 net pens. While the performance of the prototype was the primary objective, it was noted that the algorithms managed to filter out disturbances such as the fish swimming between the vehicle and the net. It was also noted that fish were not affected by the presence and operation of the drone, and calmly swam near to it.

Increased monitoring of the production environment

In **Croatia**, the biggest aquaculture producer has developed risk analysis for specific farm locations (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 integrated monitoring tool and decision support system has been developed and tested. This 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 ([44]) and the software is being provided to operators.

In **France**, in the Étang de Thau (a coastal lagoon on the Mediterranean), higher temperatures encourage algae growth, which decreases the available oxygen, which in turn negatively affects oyster production. In a joint project with companies, producers are using sensors to identify areas with low oxygen, and using oxygen injection techniques to compensate.

([42]) https://www.programapleamar.es/proyectos/gloria-global-change-resilience-aquaculture
([43]) https://www.programapleamar.es/proyectos/gloria-2-global-change-resilience-aquaculture-2
([44]) Chatziantoniou et al, 2023.

4.4 Infrastructure and system development

On France's 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.

Another measure being considered is the priming or conditioning of molluscs (exposing juveniles to seawater at high temperature), which seems to help build molluscs' resilience to heatwaves.

Better use of water and new 'in-pond' production systems in land-based production 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 covered by photovoltaic panels. The energy produced can be channelled 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 fertilisers present in the pond substrate or, to give an example in Saxony, one full pond is stocked instead of two half-empty ones.

Other measures under discussion are to increase the use of partial recirculation systems for multiple purposes and to decrease water demand by using climate resilient species and strains. A national Aquaculture Network funded under the European Maritime and Fisheries Fund (EMFF) was created in Germany to provide advice to SMEs on the management of water use on a case-by-case basis.

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 through the intensive production of new species.

New systems for mollusc culture

In **Denmark**, new systems are being evaluated for bivalve mollusc culture, such as a height-adjusted modular mussel farming system that can be submerged on demand to avoid: (1) surface weather conditions such as storms or ice; or (2) predators (e.g. eider ducks).

4.5 Location planning and relocation

Background/Challenges

Changes in water quality (physical and chemical) at the aquaculture production sites can affect productivity in various ways (e.g. poorer growth, increased FCR, decreased 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 zones within it where fish could be moved to avoid mass mortality.

4.5 Location planning and relocation

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.

An opportunity arising from these challenges lies in the potential of farming the current species in new locations. This could help expand production to new areas and sites that are better suited for production.

Proposed solutions/Adaptation measures

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

For inland production, rather than relocating the farms, the focus is on maintaining the quantity and quality of input water but using less water more efficiently and/or reducing losses. Many Member States 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 Commission staff working documents on 'Planning of space and access to water for marine aquaculture' and 'Access to space and water for freshwater and land-based aquaculture' provide examples of good practices for the planning of aquaculture areas and sites, including the identification of potential new areas/sites with lower climate change impacts, where existing farms could be relocated to ([45]).

As part of the set of Copernicus Marine Service tools, PerfeCt - Performance of Aquaculture under Climate change ([46]) is an approach to answer the 'What if?' question when establishing and/or adapting aquaculture sites in light of climate change.

This modular web application integrates a process-based modelling of fish growth, which builds on the 'dynamic energy budget' theory. It also includes an innovative index to identify vibriosis disease risk. It is incorporated into the Geographic Information System (GIS) framework to estimate relative changes to three simple aquaculture performance factors: time-to-market, feed 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:

- making stakeholders aware of future conditions relevant to aquaculture;
- providing predictions for a range of commercially important species and a range of climate change scenarios;
- assisting in the selection of existing aquaculture sites or a 10x10km 'zone of aquaculture interest' (currently in the Mediterranean Sea).

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

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

4.5 Location planning and relocation

Examples of good practices in EU Member States and other countries

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 uses a combined species production system for fresh locally available vegetables. 'Urban aquaponic farming' is an example of location planning that can provide fresh consumer products and tailor them to local market demand. 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 ([47]) has developed a numerical model that can be used 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 high accuracy in predicting local hydrodynamics, nutrient transport and water quality. Two simulations of historic and future conditions were carried out to put in place a Suitability Index capable of identifying the most appropriate sites to exploit two bivalve species (clam and oyster), considering both winter and summer seasons. The estuary's northernmost region has the best conditions for farming bivalves 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 an increase in chlorophyll-a concentration along the estuary.

In **Greece**, a decision support software (DSS) has been developed (ClimeGreAq) ([48]) in collaboration with stakeholders. The DSS simulates and visualises the effects of climate change on fish and farm economics, and may be used by stakeholders including farmers, producer organisations, regional administrations and national authorities to support decisions on how to reply to questions ranging from selecting appropriate farming locations and designating zones for aquaculture activities, to developing national climate adaptation plans.

4.6 Management of the introduction of non-native species

Background/Challenges

As climate effects intensify, the genetic selection of existing species or the introduction of new species better adapted to environmental conditions are options that many operators and Member States 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 the introduction for aquaculture purposes of alien and locally absent species. This system allowsto assess and minimise the possible impact of these species and any associated non-target species on aquatic habitats before their introduction.

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

([47]) Pereira *et al*. (2023).
([48]) Stavrakis's-Zachou et al., 2021.

of concern for the EU and a set of measures to prevent, minimise 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 with introducing 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 such introductions in the Mediterranean Basin, the General Fisheries Commission for the Mediterranean (GFCM) of the Food and Agriculture Organisation of the United Nations (FAO) produced, in 2023, guidelines on principles and minimum common criteria to address the challenges (GFCM guidelines).

The guidelines include 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), applications for authorisations and risk-management measures. A model template for an authorisation application is included as an annex to the guidelines.

The guidelines recommend a unified 'reference' method or system for the classification and scoring of the risk/impact of non-indigenous species. They suggest the EICAT framework ([49]) or the Harmonia+ rating system ([50]), which provide clear guidance for determining the impact of introducing species on biodiversity and presenting it as a score in risk assessments.

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

Examples of good practices in EU Member States and other countries

The following examples are taken from the 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.

([49]) Blackburn et al. 2014 and Hawkins et al. 2015.
([50]) D'hondt et al. 2015.

4.6 Management of the introduction of non-native species

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 cover cases where 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. The main purpose of the contingency plan is to facilitate a rapid response to restrict the spread of pathogens and increase the likelihood that they can be contained and eradicated.

If such an (escape) event occurs, the contingency plan should be implemented immediately and the authorisation 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 minimise their impacts;
- carried out by a body appointed by the competent authority in three phases: (1)-baseline monitoring study prior to introduction; (2) continued monitoring after release into aquaculture facilities; and (3) longer-term monitoring following the scale-up of farming activities.

The monitoring is recommended to be carried out for at least 2 years, or for at least one complete generation cycle of the species concerned.

Most Member States producing non-native species are doing so in RAS, which not only provides 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 African catfish, tilapia and shrimp.

5 KNOWLEDGE AND INNOVATION GAPS & INDUSTRY/POLICY RECOMMENDATIONS

5.1 Research and innovation gaps and needs

While more and more knowledge is being generated on the specific effects of climate change on aquaculture, and despite climate-related projects supported by the EU, there are still gaps to be filled. The knowledge gaps for cold water marine aquaculture of fish and bivalve mollusc were reviewed in a 2020 study ([51]). Other research needs were outlined during the CEN workshop mentioned in Chapter 4 and have been raised by stakeholders and experts. These include:

Forecasting and monitoring

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

Environmental assessment

- Effects of climate change on the environmental impacts of aquaculture – e.g. the assimilative capacity of receiving water bodies.
- The combined and/or cumulative effect of 'individual' parameters and stressors and an assessment of opportunities that climate change might offer.
- 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 under 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 (bivalve mollusc) as well as on the growth and survival of farmed bivalve mollusc species.
- Breeding programmes for building climate change resilience in farmed species.

Disease management

([51]) Collins et al. (2020).

- Effects of climate change and ocean acidification on pathogens, disease development and antimicrobial resistance, and on complex disease outcomes.
- 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 use (where necessary) 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), to maintain health status during periods of rapid temperature change and 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.
- Assessment of the risks to the industry, which is increasingly impacted by native and non-native species acting invasively (for example the proliferation of sea squirts on bottom mussel beds, or blue crabs on clam beds), causing very extensive mortality by predation.

5.2 Recommended adaptation measures for the industry

The adaptation measures listed below are recommended to be implemented by industry producer organisations, other sector operators and individual companies. These can also be included in Member States' adaptation programmes, accompanied by support measures (e.g. financial, research), for the industry.

- Encourage industry associations and breeding companies (for all species) to focus on a selection of climate-related traits, including the overall robustness of juveniles, temperature tolerance and disease resistance.
- Monitor fish and mollusc health, performance, welfare, and behaviour (using real-time / in-situ tools) to better understand short-term climate effects and quantify their impact on production. This monitoring includes:
    - 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 (stocking, harvesting, restocking);
    - cleaning processes in line with increased biofouling.
- Increase and further develop the use of aerators and other oxygen supply techniques.
- Set up new, energy efficient, cooling and recirculation systems for bivalve molluscs, for pre-harvest conditioning (previously done in special finishing ponds) and depuration.

5.3 Policy recommendations

The following adaptation measures can be adopted by competent authorities in Member States:

- Allocate funds to address research gaps that are considered a priority for that country, in consultation with aquaculture stakeholders and scientific experts.

- Set up or upgrade monitoring programmes (with standardised format/content and easy access to pooled results by producers and operators), including:
  - 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 bivalve molluscs as a bio-indicator of the quality of waters, where these molluscs are farmed, not only with respect to health and survival, performance and growth, but also to reproductive capacity. Mollusc producers may be considered as climate change custodians of the climate impacts they perceive.

- 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.

- As part of spatial planning:
  - Identify sites for the potential relocation or reallocation of aquaculture activity. This would entail identifying and establishing AZAs where the critical affecting parameters of climate change are less abrupt and hence enable aquaculture production to adapt to changes more easily.
  - Explore and promote co-location with other marine/maritime activities (for example aquaculture and wind farms).

- Adequate financing for climate adaptation measures, including support for the sector's transition to reinforce its resilience, productive and environmentally stable credentials.

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

ANNEX I: REFERENCES

Blackburn, T.M., Essl, F., Evans, T., Hulme, P.E., Jeschke, J.M., Kuhn, I., Kumschick, S., Markova, Z., Mrugała, A., Nentwig, W., Pergl, J., Pysek, P., Rabitsch, W., Ricciardi, A., Richardson, D.M., Sendek, A., Vila, M., Wilson, J.R.U., Winter, M., Genovesi, P. & Bacher, S. (2014). *A unified classification of alien species based on the magnitude of their environmental impacts*. PLoS Biol 12(5): e1001850. https://doi.org/10.1371/journal.pbio.1001850

Byrne M, Foo SA, Ross PM, Putnam HM (2020) *Limitations of cross- and multigenerational plasticity for marine invertebrates faced with global climate change*. Global Change Biology 26: 80-102. https://doi.org/10.1111/gcb.14882

CEN Workshop Agreement (CWA 17518:2020). *Good practice recommendations for making Climate Adaptation Plans for fisheries and aquaculture*. https://genorma.com/en/project/show/cen:proj:71297

CERES Deliverable 4.2. *Report on minimising economic losses, opportunities, and challenges for aquaculture in Europe*.

Chatziantoniou, A.; Papandroulakis, N.; Stavrakidis-Zachou, O.; Spondylidis, S.; Taskaris, S.; Topouzelis, K. Aquasafe: *A Remote Sensing, Web-Based Platform for the Support of Precision Fish Farming*. Appl. Sci. 2023, 13, 6122. https://www.mdpi.com/2076-3417/13/10/6122

CLIMEFISH Deliverable 4.3. *Climate-related Risks and Opportunities for Fisheries and Aquaculture in Europe*.

CLIMEFISH Deliverable 6.2. *Roadmap for implementation of recommendations of the ClimeFish DSF*.

Collins, C., Bresnan, E., Brown, L., Falconer, L., Guilder, J., Jones, L., Kennerley, A., Malham, S., Murray A. and Stanley, M. (2020). *Impacts of climate change on aquaculture*. MCCIP Science Review, pp. 482-520. https://dspace.stir.ac.uk/retrieve/935c2493-94f2-48c6-b7a6-870f35dd39c0/21_aquaculture_2020.pdf

D’hondt, B., Vanderhoeven, S., Roelandt, S., Mayer, F., Versteirt, V., Adriaens, T., Ducheyne, E., San Martin, G., Grégoire, J-C., Stiers, I., Quoilin, S., Cigar, J., Heughebaert, A & Branquart, E. (2015). *Harmonia+ and Pandora+: risk screening tools for potentially invasive plants, animals, and their pathogens*. Biological Invasions. DOI 10.1007/s10530-015-0843-1.

European Commission, Joint Research Centre, Sanchez-Jerez, P., Raftoyannis, Y., Riihimäki, M. et al., *EU bioeconomy monitoring system indicator update*, Mubareka, S.(editor), Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2760/19269

European Commission, Directorate-General for Maritime Affairs and Fisheries, *Community-led local development and the blue economy*, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2771/392

EUMOFA. (2020). Study report. *Recirculating Aquaculture Systems*. doi:10.2771/66025 https://www.eumofa.eu/documents/20178/84590/RAS+in+the+EU.pdf/c9ee5f4c-a41d-160e-e9cc-17a19228d669?t=1606927186649

FAO. (2023). *Guidelines on assessing and minimising the possible impacts from the use of non-indigenous species in aquaculture*. General Fisheries Commission for the Mediterranean. Rome. https://doi.org/10.4060/cc3207en

FAO. (2022). *FAO Strategy on Climate Change 2022-2031*. Rome. https://www.fao.org/3/cc2274en/cc2274en.pdf

FAO. (2022). Technical Paper 682. *World review of capture fisheries and aquaculture insurance* https://www.rfilc.org/wp-content/uploads/2022/04/World-review-of-capture-fisheries-and-aquaculture-insurance-2022.pdf. Regional report for Europe starts on page 157.

Falconer, L.; Telfer, T.C.; Garrett, A.; Hermansen, Ø.; Mikkelsen, E.; Sætre Hjøllo, S.; McAdam, B.J.; Ytteborg, E. 2022. *Insight into real-world complexities is required to enable effective response from the aquaculture sector to climate change*. PLOS Climate https://doi.org/10.1371/journal.pclm.0000017

Lynne Falconer, Lars Olav Sparboe, Trine Dale, Solfrid Sætre Hjøllo, Orestis Stavrakidis-Zachou, Øivind Bergh, Philip James, Nikos Papandroulakis, Velmurugu Puvanendran, Sten Ivar Siikavuopio, Øyvind Johannes Hansen, Elisabeth Ytteborg. *Diversification of marine aquaculture in Norway under climate change*. Aquaculture, Volume 593, 2024, https://doi.org/10.1016/j.aquaculture.2024.741350

Federation of European Aquaculture Producers (FEAP) Annual report. (2022). https://feap.info/wp-content/uploads/2023/03/feap-annual-report-feap-2022.pdf

Hawkins, C.L., Bacher, S., Essl, F., Hulme, P.E., Jeschke, J.M., Kühn, I.; Kumschick, S., Nentwig, W., Pergl, J., Pyšek, P., Rabitsch, W., Richardson, D.M., Vilà, M., Wilson, J.R.U., Genovesi, P. & Blackburn, T.M. (2015). *Framework and Guidelines for Implementing the Proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT)*. Diversity and Distributions, 21 (1360-1363).

Hill, M.J.; Hassall, C.; Oertli, B.; Fahrig, L.; Robson, B.; Biggs, J.; Samways, M.; Usio, N.; Takamura, N.; Krishnaswamy, J.; et al. (2018) *New policy directions for global pond conservation*. Conserv. Lett., 11, e12447, doi:10.1111/conl.12447.

Marine Climate Change Impacts Partnership (MCCIP). (2018). *Climate change and marine conservation. Saline lagoons*. https://www.mccip.org.uk/sites/default/files/2021-07/mccip-saline-lagoons-report-card_second-run_v3.pdf

Palásti, P., Kiss, M., Gulyás, Á., Kerepeczki, É. (2020) *Expert Knowledge and Perceptions about the Ecosystem Services and Natural Values of Hungarian Fishpond Systems*. Water, 12. 2144.

Panicz Remigiusz, Beata Całka, Alhambra Cubillo, João G. Ferreira, James Guilder, Susan Kay, Adam Kennerley, André Lopes, João Lencart e Silva, Nick Taylor, Piotr Eljasik, Jacek Sadowski, Paulina Hofsoe-Oppermann and Sławomir Keszka. *Impact of climate-driven temperature increase on inland aquaculture: Application to land-based production of common carp (Cyprinus carpio L.) 2022*. Transboundary and Emerging Diseases Vol 69. Issue 5. Pages e2341-e2350. https://doi.org/10.1111/tbed.14577

Pereira, H, Picado, A, Sousa, M., Brito, A., Biguino, B., Carvalho, D., Dias, J.M. (2023). *Effects of climate change on aquaculture site selection at a temperate estuarine system*. Science of The Total Environment, 888 (164250). https://doi.org/10.1016/j.scitotenv.2023.164250

Pham, T.T.T., Friðriksdóttir, R., Weber, C.T, et al. (2021). *Guidelines for co-creating climate adaptation plans for fisheries and aquaculture*. Climatic Change, 164 (62). https://doi.org/10.1007/s10584-021-03041-z

Stavrakidis-Zachou, O.; Lika, K.; Anastasiadis, P.; et al. (2021). *Projecting climate change impacts on Mediterranean finfish production: a case study in Greece*. Climatic Change, 165 (67). https://doi.org/10.1007/s10584-021-03096-y

Stavrakidis-Zachou, O, Astrid Sturm, Konstadia Lika, Frank Wätzold and Nikos Papandroulakis (2021). ClimeGreAq: *A software-based DSS to support aquaculture production in Greece under climate change* Environmental Modelling and Software. https://doi.org/10.1016/j.envsoft.2021.105121

Van Duinen, R., Rivière, C., Strosser, P., et al. (2023). *Algae and climate: final report*, Publications Office of the European Union. https://data.europa.eu/doi/10.2926/208135

ANNEX II: METHODOLOGY

This document was developed with the support of the EU Aquaculture Assistance Mechanism (EU AAM) ([29]). Relevant and recent information on the effects of climate change on EU and global aquaculture was drawn from desk research and a review of the scientific literature, notably guidelines and handbooks produced by the Food and Agriculture Organisation of the United Nations (FAO), scientific publications and case studies. Further general information was gathered from the European Climate Adaptation Platform (Climate-ADAPT) (see Annex III).

Information was also drawn from the outcomes of EU-funded research projects, in particular 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). This information was complemented by climate-related deliverables and reports from more recent and ongoing EU projects (e.g. FutureEUAqua, AquaVitae, DOGMATiCC, GAIN, iFishIENCi, PerformFish and SOCLIMPACT amongst others).

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 drawn from aquaculture good practices (for example, best aquaculture practices (BAP), GlobalGAP and the Global Seafood Alliance) and standards documents (for example, related to equipment).

The effects of climate change are in many cases outpacing our knowledge on the way in which they develop. Therefore, some project outputs based on scenarios and models that are several years old may not necessarily reflect the current situation faced by the sector. This issue was addressed in the document.

The CEN Workshop Agreement (CWA 17518:2020) was the principal source for Section 4. 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 multiannual national strategic plans for aquaculture (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 focused on identifying 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 analysing the information gathered through the data collection activities mentioned above, good practices covering the diversity of EU aquaculture were identified and compiled.

Several rounds of consultation with climate experts also took place at different stages in the preparation of this document. For example, a workshop was organised in Brussels in October 2023 specifically to examine and discuss the draft document.

ANNEX III: The EU Climate-ADAPT portal

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

- expected climate change in Europe;
- current and future vulnerabilities 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 data and information and makes it available to the public through the following user-friendly tools and web pages:

- A database with 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.
- A web page on adaptation by sector, including marine and fisheries, agriculture, biodiversity, water management and many others.
- Country profiles of EEA members.
- Cases studies on key aspects in the implementation cycle of adaptation measures.
- An adaptation support tool.