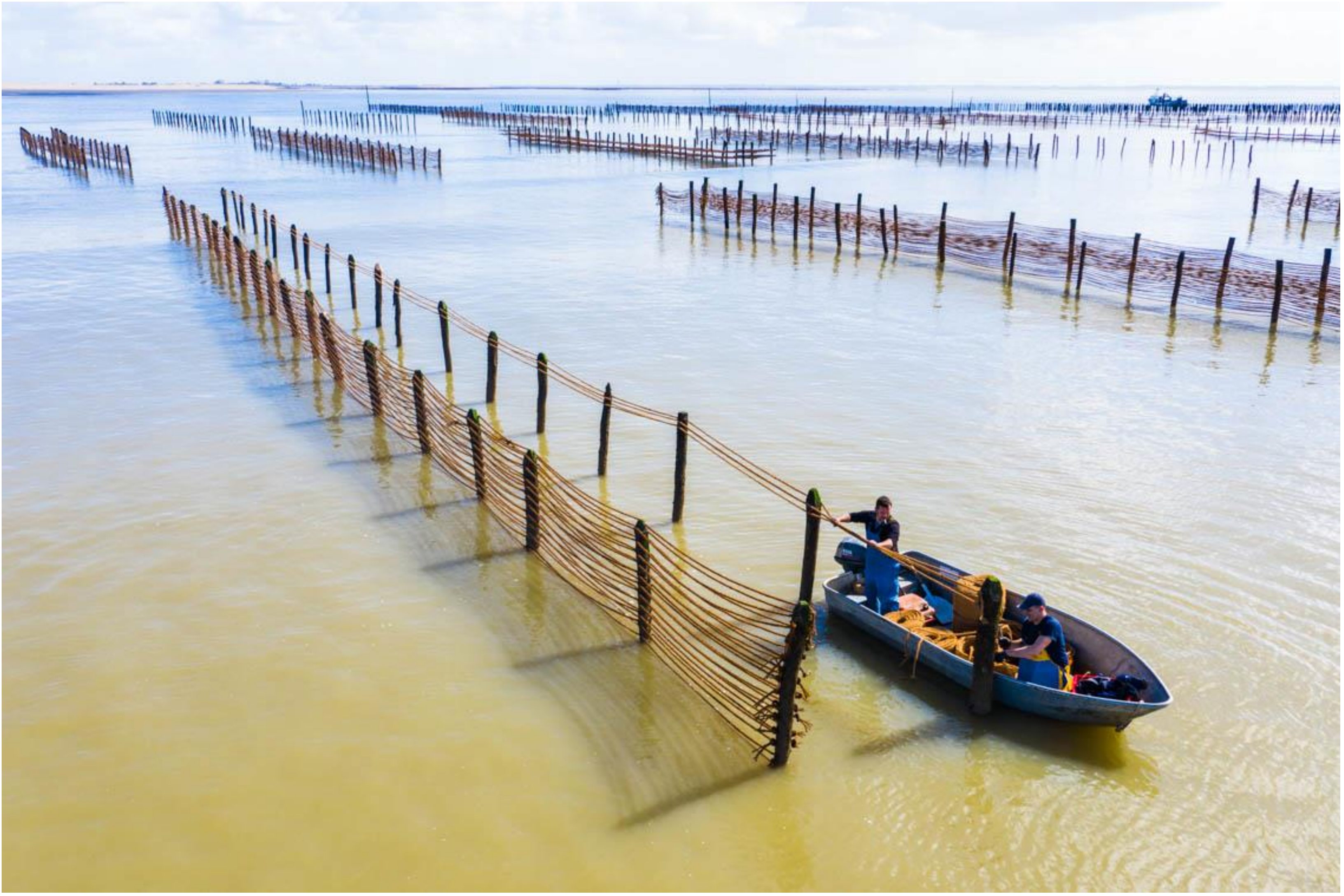


European Aquaculture: Climate Change Adaptation and Mitigation

Advice to the Aquaculture Advisory Council

Final Report

October 2022

Report Information

This report has been prepared with financial support from the Aquaculture Advisory Council (AAC) and the European Commission. The views expressed in this study are purely those of the authors and do not necessarily reflect the views of AAC nor the Commission, nor in any way anticipates their future policy in this area. The content of this report may not be reproduced, or even part thereof, without explicit reference to the source.

Suggested citation: Huntington, T (2022). European Aquaculture and Climate Change Adaptation and Mitigation - Advice to the Aquaculture Advisory Council. Final Report produced by Poseidon Aquatic Resources Management Europe Ltd for the AAC. 27 pp plus appendices.

Client: The Aquaculture Advisory Council

Version: Final Report

Report ref: 1770-ECE/R/02/C

Date issued: 24 October 2022

Author contact: tim@consult-poseidon.com

Acknowledgements: The author would like to acknowledge with thanks the AAC Secretariat and study Focus Group.

Photo credit: Sébastien Husté

POSEIDON
AQUATIC RESOURCE MANAGEMENT

Poseidon Aquatic Resource Management Europe Ltd
71 Lower Baggot Street
Dublin DO2 P593, Republic of Ireland

europe@consult-poseidon.com
consult-poseidon.com

CONTENTS

Figures and Boxes

Figures

Boxes

Executive Summary

Background and Purpose

The EU is a major food producer and exporter but does rely on imports of feed protein for animal and fish livestock alike. EU aquaculture has not shown the same spectacular rate of growth as seen in SE Asia, but still grew 11% in volume and 40% in value over 2010 – 2019 and represents around 30% of the EU's seafood production.

Climate change, caused by largely anthropogenic-driven global warming, is already demonstrating its potential to challenge existing food production systems in the EU that are already being impacted by geo-political turbulence. Aquaculture is no exception, and it is important that sector planners and operators are prepared and enabled to increase their resilience to climate change impacts, as well as adapting to the changing conditions in order to maintain environmentally and economically sustainable aquaculture in Europe.

This report examines the potential solutions for adapting to – and mitigating against – the impact of climate change on EU aquaculture. It also examines the resilience of aquaculture to climate change compared to equivalent terrestrial food production systems. It concludes with a series of recommendations aimed at the Commission and to aquaculture stakeholders across the EU.

EU policy framework in the context of aquaculture and climate change

The European Climate Law (2021) sets into legislation the objective of a climate-neutral EU by 2050 and a reduction of net greenhouse gas emissions by at least 55% by 2030 from 1990. The Farm to Fork Strategy is aimed at a neutral or positive environmental impact from EU food production and to help to mitigate climate change and adapt to its impacts. A number of other EU policies and directives e.g. the WFD, MSFD and IMP also consider the issue of climate change in a maritime context. More specific to aquaculture, the new (2021) EU strategic guidelines for a more sustainable and competitive EU aquaculture includes considerable detail on 'Climate-change adaptation and mitigation'. Other EU directives, such as for MSP also recognise the direct linkage between sustainable aquaculture development and the impact of climate change.

The EU has also supported a number of ground-breaking studies to examine the potential impact of climate change in European aquaculture and initiate development of guidance and tools for its adaptation and mitigation. Horizon 2020 has funded two key projects, CERES and ClimeFish. Between them they have produced a number of comprehensive case studies for key aquaculture finfish, shellfish and seaweed species across Europe and have produced a number of guidance documents and tools to assist decision-makers and operators alike.

In order to identify suitable mitigation points for avoiding or reducing aquaculture's contribution to GHG emissions, life cycle analysis approaches have been developed specifically to estimate the carbon footprint of seafood production at different points in the value chain. This has allowed for strategic and operational changes to be made to reduce GHG emissions across the lifecycle, from aquafeed production through to product distribution. It also heralds the possibility of common standards for declaring the carbon footprint of different aquaculture products for consumers.

Brief review of climate change and its potential impact on EU aquaculture

Short-term climate change impacts can cause loss of production from extreme events such as floods, increased risks of diseases, parasites and harmful algal blooms. Climate-driven changes in temperature, precipitation, ocean acidification, incidence and extent of hypoxia and sea level rise, amongst others, are also expected to have long-term impacts in the aquaculture sector at multiple scales.

A climate vulnerability assessment of European aquaculture conducted by CERES suggests that suggests that the direct effects of climate-driven warming (through 2050) will have limited, direct negative impacts on species currently cultured in most areas, although short-term and likely highly disruptive events are to be expected. Most of the vulnerability to Europe's aquaculture sector stems from effects that are either indirect or are related to differences in the adaptive capacity based on the method of cultivation. This suggests that the sector might be particularly sensitive to the future development of feed costs, returns and marketing options compared to future environmental change.

There is limited evidence of climate change preparedness and adaption by EU aquaculture to date. However there are strong signs of preparation in the form of forecasting e.g. via CERES and ClimeFish and setting the governance framework through the new EU guidelines for the sustainable development of EU aquaculture and the Member State preparation of MANPs and EMFAF operation programmes to identify and fund climate change adaption and mitigation measures over the next 5 – 10 years.

Potential solutions to a more climate change resilient EU aquaculture sector

Although climate change has the potential to impact current EU aquaculture production patterns, its effects will also provide opportunities for 'realigning' the geography and nature of current European aquaculture and stimulating a diversification into new, possibly lower-trophic species and IMTA systems. There are also potential on-farm solutions to adapting to more variable or extreme environmental conditions, as well as wider solutions for building resilience into aquaculture, for instance through selective breeding and better biosecurity.

In terms of climate change mitigation, research shows that the greatest opportunities for high-volume reductions in greenhouse gas (GHG) emissions are likely to come from changes in upstream and downstream parts of the supply chain. In particular, the use of lower carbon raw materials for aquafeed will be key. LCA approaches like Product Environmental Footprint analysis will also allow the mitigation intervention points over the whole value chain to be identified. This will in turn allow carbon-related costs to added to conventional commercial factors for decision-making, both for operators as well as Member State sustainable aquaculture sector development planning.

Resilience of EU aquaculture compared to terrestrial food production systems

Despite some particular vulnerabilities, both aquatic and terrestrial livestock production are relatively resilient to the impacts of climate change, especially when compared to plant-based agriculture. Indeed, as has been well documented, their similar dependence upon high protein feeds mainly of a terrestrial origin is a common indirect vulnerability. Crop farming, as well as some land-based aquaculture, is more vulnerable largely due to their dependence upon ample and stable water supplies. This is likely to lead to considerable changes in crop agriculture patterns in southern Europe over the next few decades.

In terms of mitigating the EUs contribution to GHG emissions, moving some aquatic and most terrestrial livestock production to a lower carbon approach is vital as they are disproportionately high GHG emitters, due to their dependence upon high protein feeds and the metabolic characteristics of the livestock species involved (e.g. salmonids, sea bass and sea bream in aquatic systems and beef, pigs and poultry in terrestrial systems). This said, the emissions intensity of most finfish lies between 4 and 6 kg CO2-e/kg carcass weight (cw) whilst beef is over 40 CO2-e/kg cw and sheep 30 CO2-e/kg cw (MacLeod *et al*, 2020), so the onus will be on the terrestrial livestock industry to respond accordingly.

Consumers will have an important role in shaping market forces towards lower-carbon food production. Therefore efforts to ensure they are informed of the full carbon footprint of different food choices will be essential.

Finally we consider that the wider EU policy framework to move towards carbon-neutrality by 2050 is now in place, together with the strategic planning and funding mechanisms to support this transition. It is now up to it is up to the Member States - both in terms of the public and private sectors – to ensure this ambition is realised.

Acronyms used

AAC .... Aquaculture Advisory Group
aCAP .... aquaculture climate adaptation plan
AI .... artificial intelligence
AIP .... Aquaculture Improvement Project
AQUAPEF .... Promote the effective implementation of the Product Environmental Footprint in the Mediterranean aquaculture sector
ASC .... Aquaculture Stewardship Council
BPF .... best practice framework
CAP .... Common Agriculture Policy
CC .... climate change
CERES .... Climate change and European Aquatic RESources
CHIP .... Coupled Model Intercomparison Project
Climate-ADAPT .... European Climate Adaptation Platform
CO_2-e .... carbon dioxide equivalent
cw .... carcase weight
DSS .... decision-support system
EEA .... European Environment Agency
EI .... emissions intensity
EMFAF .... European Maritime, Fisheries and Aquaculture Fund
EU .... European Union
EUMOFA .... European Market Observatory for fisheries and aquaculture
FAMENET .... Fisheries and Aquaculture Monitoring, Evaluation and Local Support Network
FAO .... Food and Agriculture Organisation
FEFAC .... European Feed Manufacturers' Federation
GESAMP .... Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GWP .... global warming potential
JRC .... Joint Research Centre
HAB .... harmful algal bloom
IMTA .... integrated multi-trophic aquaculture
LCA .... life cycle analysis
LULUCF .... land use, land use change and forestry
MANP .... multi-annual national plan
MSC .... Marine Stewardship Council
MSFD .... Marine Strategy Framework Directive
Mt .... metric tonne
NDC .... nationally determined contribution
OMC .... Open Method of Coordination (of aquaculture)
PAS .... Publicly Available Specification
PEF .... Product Environmental Footprint
PEFCR .... Product Environmental Footprint Category Rules
RAS .... recirculated aquaculture system
SOP .... standard operating procedure
USD .... United States dollar
WCRP .... World Climate Research Programme
WFD .... Water Framework Directive

1. Background and Purpose

1.1 Background

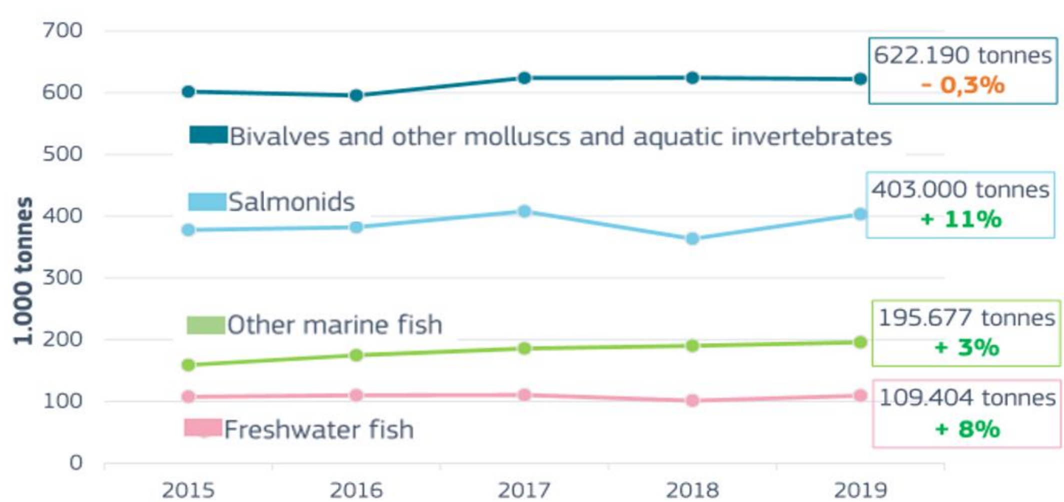
The European Union (EU) is a net food exporter and top agri-producer, producing 336 billion euros (EUR) worth of agricultural goods (mainly vegetables 26.5%, cereals 21% and fruit 14.1%) and 141 billion EUR of animals (mainly pigs 24.9%, cattle 17.3% and poultry 12.2%) in 2020 (see Figure 2 **in Appendix B**). Whilst largely self-sufficient for many agricultural products, it is a net importer for some specific products such as feed protein. This vulnerability, together with high input costs, such as fertilisers and fossil energy, is causing production challenges for farmers and risks driving up food prices. Underlying this geo-political uncertainty is the longer-term and more fundamental challenge of climate change and is impacts on global food production.

The EU-28 is currently ranked fifth in the world in terms of fisheries production, producing around 4.8 million metric tonnes (mt) of catches and 1.4 million mt from aquaculture (EUFOMA, 2021). In 2020 the EU trade of fisheries and aquaculture products[1] was the highest in the world, totalling EUR 31.17 billion and 8.72 million mt. Imports amounted to EUR 24.21 billion and 6.15 million mt and exports amounted to 2.21 million mt.

Looking at aquaculture in particular, the EU imports around 1.79 million mt of farmed products, consumes 2.9 million mt and exports 0.26 million mt. In 2019, EU aquaculture production reached a total of 1.37 million mt, with a value of EUR 4,99 billion. This is an increase of 130,554 mt or 11% from 2010 to 2019, while its value grew by 40% in real terms, an increase of almost EUR 1.43 billion.

Almost half of EU aquaculture production volume consists of bivalves and other molluscs and aquatic invertebrates, mainly thanks to the productions of mussel in Spain and oyster in France. Salmonids and the grouping "other marine fish" follow, with salmonids mainly including salmon and trout, and other marine fish mainly including gilthead seabream and European seabass. Freshwater species come next, largely comprising carps (see **Figure 1**).

Figure 1: Volumes of main farmed species groups in the EU and % change 2018 / 2019



Source: EUMOFA, based on EUROSTAT (online data code: fish_aq2a) and FAO data.

[1] Presented here as the combined amounts of imports and exports with third countries

Farmed fin and shellfish represent an important source of healthy protein, with farmed salmon containing 20.4 g protein / 100 g portion, sea bass 20.4 g protein / 100 g portion, common carp 17.8.4 g protein / 100 g portion and mussels 12.1 g protein / 100 g portion[2].

Climate change refers to long-term shifts in temperatures and weather patterns. These shifts may be natural, such as through variations in the solar cycle. Since the 1800s human activities have been the main driver of climate change, primarily due to burning fossil fuels like coal, oil and gas. The EU is the world's third largest greenhouse gases emitter after China and the United States and followed by India, Russia and Japan. Greenhouse gas (GHG) concentrations are at their highest levels in two million years and emissions continue to rise. As a result, the Earth is now about 1.1°C warmer than it was in the late 1800s. The last decade (2011-2020) was the warmest on record.

Within the EU, the energy sector was responsible for 77% of greenhouse gases emissions in the EU in 2019, followed by agriculture (11%), industry (9%) and the waste sector (3%). In 2008 the EU set a target to cut GHG emissions by 20% by 2020 compared to 1990 levels. This was updated in 2021 to at least 55% by 2030 compared to 1990. Some progress has been made - in 2015 there was already a decrease of 22% compared with 1990 levels.

Europe is warming faster than the global average. The mean annual temperature over European land areas in the last decade was 1.94 to 2.01°C warmer than during the pre-industrial period. Particularly high warming has been observed over eastern Europe, Scandinavia and at eastern part of Iberian Peninsula[3].

Projections from the CMIP 6[4] initiative suggest that temperatures across European land areas will continue to increase throughout this century at a higher rate than the global average. Land temperatures in Europe are projected to increase further by 1.2 to 3.4° under the SSP1-2.6 scenario and by 4.1 to 8.5°C under the SSP5-8.5 scenario (by 2071-2100, compared to 1981–2010). The highest level of warming is projected across north-eastern Europe, northern Scandinavia and inland areas of Mediterranean countries, while the lowest warming is expected in western Europe, especially in the United Kingdom, Ireland, western France, Benelux countries and Denmark.

The impacts of climate change are already being felt in the forms of drought, higher incidences of extreme rainfall and increasing sea water temperatures. These in turn have severe consequences for EU food production with failed or destroyed crops, lower yields and increased vulnerability to diseases and pests. These impacts are not uniform across the geography of the EU. Projections from the EEA show that the Mediterranean will be particularly affected with large increases in heat extremes and other climatic hazards (see infographic in **Figure 3: Climate change impacts in Europe**). The EU's coastal zones will see sea level rise, increases in sea surface temperatures and acidity and increasing numbers of marine 'dead zones'.

---

[2] Salmon, sea bass & mussels: https://www.seafish.org/promoting-seafood/health-benefits-of-seafood/#nutritional-profiles-for-fish-and-shellfish; common carp https://www.nutrition-and-you.com/common-carp.html

[3] https://www.eea.europa.eu/ims/global-and-european-temperatures

[4] World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP)

1.2 Scope and Purpose

This study examines the *impacts of climate change* on aquaculture, how the sector might *adapt to these impacts* and the possible contribution of aquaculture *to mitigate climate change.* These three elements need to be considered separately.

- **Climate change impacts** examines how global warming affects climates, the resulting impacts on the physical and biological environments and how this might affect current EU aquaculture systems.
- **Climate change adaptation** means altering and diversifying aquaculture systems to both (i) make them more resilient to the impacts of climate change and (ii) adapt to changes in the climate and associated conditions in order to maintain environmentally and economically sustainable aquaculture in Europe.
- **Climate change mitigation** means avoiding and reducing aquaculture's contribution of emissions of heat-trapping greenhouse gases e.g. from animal respiration, refrigeration and transportation.

This report summarises the findings of this study and is intended to provide the basis for advice to the European Commission, to the EU Member States and to other European aquaculture stakeholders on forming their climate change adaptation and mitigation strategies. The geographical focus is on the EU-28 Member States, but also takes into account the experience and lessons learned from elsewhere in Europe and the world.

Funding and guidance have been provided by the Aquaculture Advisory Council (AAC).

Box 1: Synthesis - Background and Purpose

The EU is a major food producer and exporter but does rely on imports of feed protein for animal and fish livestock alike. EU aquaculture has not shown the same spectacular rate of growth as seen in SE Asia but still grew 11% in volume and 40% in value over 2010 – 2019 and represents around 30% of the EU's seafood production.

Climate change, caused by largely anthropogenic-driven global warming, is already demonstrating its potential to challenge existing food production systems in the EU that are already being impacted by geo-political turbulence. Aquaculture is no exception, and it is important that sector planners and operators are prepared and enabled to increase their resilience to climate change impacts, as well as adapting to the changing conditions in order to maintain environmentally and economically sustainable aquaculture in Europe.

This report examines the potential solutions for adapting to – and mitigating against – the impact of climate change on EU aquaculture. It also examines how resilient aquaculture is against equivalent terrestrial food production systems. It concludes with a series of recommendations aimed at the Commission and to aquaculture stakeholders across the EU.

For a full list of literature cited in this document, see **Appendix A**.

For additional tables and figures, see **Appendix B**.

2. EU policy framework in the context of aquaculture and climate change

2.1 EU policy on climate change adaptation, food security and environmental management

Following adoption on a new EU *Strategy on Adaptation to Climate Change* (EC, 2021a) in June 2021, the European Council adopted the *European Climate Law*, setting into legislation the objective of a climate-neutral European Union (EU) by 2050 and a reduction of net greenhouse gas emissions by at least 55% by 2030 (from a baseline of 1990). This is an important part of the *European Green Deal* (EC, 2019), which provides an action plan to boost the efficient use of resources by moving to a clean, circular economy and restore biodiversity and cut pollution.

A component of the *European Green Deal*, the *Farm to Fork Strategy* (EU, 2020) aims to accelerate a transition to a sustainable food system that should (i) have a neutral or positive environmental impact, (ii) help to mitigate climate change and adapt to its impacts, (iii) reverse the loss of biodiversity, (iv) ensure food security, nutrition and public health. The *Farm to Fork Strategy* also refers to the new EU carbon-farming initiative under the *European Climate Pact*, as well as the regulatory framework for certifying carbon removals to be developed by the Commission, including carbon-capture services from aquaculture. Promoting aquaculture with climate-mitigation services could also be considered in the context of the nationally determined contributions (NDCs) under the *Paris Agreement* on climate change.

Other key EU policy and associated legislation relevant to aquaculture and climate change includes the *Organic Action Plan* (EC, 2021b) that specifically supports reinforcing organic aquaculture, including integrated multi-tropic aquaculture (IMTA) and the EU *Biodiversity Strategy for 2030* (EC, 2020) that foresees a more sustainable approach to economic growth following COVID-19. Aquaculture is also a major part of the EU's *Blue Economy* (EC, 2021c), that focuses on low environmental impact EU aquaculture, with a particular emphasis on algae production.

The EU *Integrated Maritime Policy* (IMP) seeks to provide a more coherent and coordinated approach to marine and maritime issues, including considering climate change. The *Marine Strategy Framework Directive* (MSFD) is the IMP's environmental pillar. Under the MSFD, and in developing their respective national marine strategies, Member States need to specify, where appropriate, any evidence of climate change impacts.

2.2 Current approaches to supporting climate change adaptation and mitigation in EU aquaculture

More specific to the aquaculture sector are the EU's strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030. Originally published in 2013 (EC, 2013), these guidelines were updated in May 2021 (EC, 2021d). There is a specific section on 'Climate-change adaptation and mitigation' that requires that dedicated sectoral adaptation strategies should address the aquaculture sector specifically and that any potential negative contribution made by aquaculture to climate change needs to be minimised. It also recognises the potential contribution of low-trophic aquaculture (such as for macroalgae and molluscs) in providing climate-mitigation services such as carbon sequestration.

Outside of this specific section, the subject of climate change underpins many of the other objectives in the guidelines. For instance maritime spatial planning (MSP) should take into account the adaptation of aquaculture to climate change, as well as the potential of certain types of aquaculture to mitigate the impact of climate change (e.g. carbon capture or preservation of ecosystems that provide for protection against extreme weather events) and or climate-adaptation services (such as nature-based coastal protection). The potential impact of climate change on fish health is also recognised, and therefore the necessity to include an undertaking of changing climate in biosecurity planning.

2.3 Examples of existing incentives and tool sets

Given the increasing attention both to the emerging and potential impact of climate change on food production in the EU, as well as the considerable contribution of agriculture to EU GHG emissions (*c*. 11%, see **Section 1.1**), there have been a number of initiatives over the last ten years to both investigate the impacts of climate change on EU aquaculture and to develop tools for the sector's adaptation and mitigation. These are briefly reviewed below.

2.3.1 Horizon 2020 projects

The EU's flagship *Horizon 2020* research programme funded two key projects to better understand the likely impacts of climate change to EU aquaculture and how the sector – at both governance and operational levels – might support adaptation and mitigation.

- **Climate change and European Aquatic RESources (CERES) 2016-2020** (https://ceresproject.eu/) investigated how climate change might affect both wild and farmed fish and shellfish species throughout European waters. They prepared 24 species and location specific case studies (e.g. #13 Seabass and sea bream in the eastern Mediterranean) that describe the likely impacts on environmental conditions, production and related economics, identified key research needs and suggested 'climate-ready solutions' (see **Figure 4** In **Appendix B** for an example) and policy directions. CERES also produce a number of other products including various research reports and geo-spatial tools that will support stakeholders anticipate and adapt to climate change in EU aquaculture.
- **ClimeFish 2016 – 2020** (https://climefish.eu/) also looked at wild fisheries and aquaculture. Whilst also including (16) case studies (e.g. C9F – Czech Republic Lakes, includes species like catfish, pike-perch, carp, whitefish) it also focused on developing climate change forecasting models to simulate and analyse changes in distribution and production in the fisheries and aquaculture sectors. Using these it worked with stakeholders to develop case-specific Management Plans that mitigate risks and utilize opportunities associated with anticipated effects of climate change on aquatic production. It also developed the *ClimeFish* Decision Support Framework and worked closely the European Climate Adaptation Platform (Climate- ADAPT[5]) to ensure its tools were available and supported after project closure.

[5] Climate-ADAPT (https://climate-adapt.eea.europa.eu/) is a 'one-stop shop' for finding climate adaptation projects and was established jointly by the Commission and the European Environment Agency (EEA).

2.3.2 Life Cycle Analyses

A key tool for focusing climate change mitigation approaches is the Life Cycle Analysis (LCA). An LCA is a method to map and quantify the environmental impacts that a product causes through its life cycle by keeping a record of mass and energy flows and maps where environmental impacts are caused. LCA is standardized by ISO in their 14000 family on environmental management. LCA is holistic by taking a complete life cycle, or a complete production system, into account and by including a complementary set of environmental impacts. Typical LCA impact categories include global warming, acidification, eutrophication and aquatic / marine / terrestrial eco-toxicity. Using outputs from LCAs enables both governance agencies and businesses to identify what processes generate GHGs through the entire aquaculture value chain and suggest how these might be reduced or mitigated. There are a number of LCA standards relevant to climate change mitigation in aquaculture including:

- The British Standards Institute (BSI) PAS 2050:2011 **Publicly Available Specification (PAS) for the assessment of the life cycle greenhouse gas emissions of goods and service**s is one of the most applied standards for GHG assessment of products globally. The PAS-2050-2 was published in 2012 (BSI, 2012) to provide guidance on the consistent application of PAS 2050:2011 to seafood and other aquatic food products[6] and has recently been updated by ISO 22948 *Carbon footprint to seafood Product category rules for finfish* (BSI, 2020).
  - As an example, a report currently being prepared for the Bord Iascaigh Mhara (BIM) in Ireland provides LCAs for salmon, rope-grown shellfish and trestle-grown oysters to estimate their carbon footprint at different stages and will provide both strategic and operational advice on how to reduce this as part of Ireland's *National Strategic Plan for Sustainable Aquaculture* (2022 – 2030).
- The EU's standardised method for assessing the ***Product Environmental Footprint*** **(PEF)** is described by the guide "*Annex to Commission Recommendation 2013/179/EU on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations*". The LCA-based PEF method quantifies the relevant environmental impacts of products (goods or services). It builds on existing approaches and international standards, aiming for better reproducibility and comparability of the results, assuming that results are based on the same Product Environmental Footprint Category Rules (PEFCR).
  - A 1.7 million EU LIFE project AQUAPEF (2018-2022) is promoting the effective implementation of the PEF approach in the Mediterranean aquaculture sector. The AQUAPEF tool calculates the environmental impact of aquaculture products in accordance with the EU PEF methodology and enables identification of the impact's causes and origins, so that decision-making based on environmental criteria becomes easier.
  - The Marine Fish PEFCR, developed in support of the EU policy for sustainable production and consumption, recently produced its PEFCR for unprocessed Marine Fish Products (Anon, 2022), including wild and farmed products.

[6] The PAS 2050-2 provides a common approach to assess GHG emissions associated with both wild caught and farmed fish products. It enables organizations to review their activities at all stages of the seafood lifecycle - from brood-stock rearing to fish capturing, farming and slaughtering, landing and auctioning, fish processing, transport and preservation.

Box 2: Synthesis - EU policy framework in the context of aquaculture and climate change

The *European Climate Law* (2021) sets into legislation the objective of a climate-neutral EU by 2050 and a reduction of net greenhouse gas emissions by at least 55% by 2030 from 1990. The *Farm to Fork Strategy* is aimed at a neutral or positive environmental impact from EU food production and to help to mitigate climate change and adapt to its impacts. A number of other EU policies and directives e.g. the WFD, the MSFD and IMP also consider the issue of climate change in a maritime context. More specific to aquaculture, the new (2021) EU strategic guidelines for a more sustainable and competitive EU aquaculture includes considerable detail on 'Climate-change adaptation and mitigation'. Other EU directives, such as for MSP also recognise the direct linkage between sustainable aquaculture development and the impact of climate change.

The EU has also supported a number of ground-breaking studies to examine the potential impact of climate change in European aquaculture and initiate development of guidance and tools for its adaptation and mitigation. Horizon 2020 has funded two key projects, *CERES* and *ClimeFish*. Between them they have produced a number of comprehensive case studies for key aquaculture finfish, shellfish and seaweed species across Europe and have produced a number of guidance documents and tools to assist decision-makers and operators alike.

In order to identify suitable mitigation points for avoiding or reducing aquaculture's contribution to EU GHG emissions, various life cycle analysis (LCA) approaches have been developed specifically to estimate the carbon footprint of seafood production at different points in the value chain. This has allowed for strategic and operational changes to be made to reduce GHG emissions across the lifecycle, from aquafeed production through to product processing and distribution. It also heralds the possibility of common standards for declaring the carbon footprint of different aquaculture products for consumers.

3. Brief review of climate change and its potential impact on EU aquaculture

This section briefly reviews the ways in which climate change might affect aquaculture production in the EU and then introduces possible approaches to their adaptation and mitigation that are explored in more detail in the following **Section 4**.

3.1 Impact and vulnerability of climate change on EU aquaculture production

Perhaps the most comprehensive synthesis of current knowledge, adaptation and mitigation options of climate change on aquaculture is from FAO (Barange *et al*., 2018). This notes both the impacts from short-term climate change impacts causing large-scale loss of production from extreme events such as floods, increased risks of diseases, parasites and harmful algal blooms. Long-term impacts can include reduced precipitation leading to increasing competition for freshwater. Climate-driven changes in temperature, precipitation, ocean acidification, incidence and extent of hypoxia and sea level rise, amongst others, are also expected to have long-term impacts in the aquaculture sector at multiple scales (Barange *et al*., 2018; Holmyard, 2014). An often unrecognised impact of climate change is on food and human safety, for example through changes in the growth rates of pathogenic marine bacteria (see Cascarano *et al*, 2021), or on the incidence of parasites, food-borne viruses and the possible emergence of zoonotic diseases.

The CERES project examined the climate vulnerability for the most valuable European aquaculture species of finfish and shellfish cultured in Europe (Payne *et al*, 2020), based on a combination of *exposure*, *sensitivity* and *adaptive capacity* (see **Figure 5** in **Appendix B**). Climate vulnerability scores ranged from 14.2 to 23.0. Countries with the lowest scores were the United Kingdom, Ireland and Sweden whereas countries that had the highest scores were Greece, Malta and Estonia (see **Figure 6**). Unpacking this more:

- **Sensitivity**[7] had the highest contribution to overall vulnerability, although countries had high or low sensitivity for different reasons. For example, aquaculture plays a relatively important role to the GDP of Malta, Cyprus and Greece. Countries heavily relying on mussels or clams also had high sensitivity scores but aquaculture often had a much smaller relative importance to GDP.
- **Adaptive capacity**[8] was the next more important influence on vulnerability and was driven by the fact that some countries (Spain, UK and then Germany, Norway, Finland, Portugal and Malta) had progressed further (in 2017) in the implementation of their climate adaptation plans and therefore had relative low scores. Spain had a high adaptive capacity due to the higher percentage of 'large' firms and strong progress on climate adaptation planning. Most countries, and in particular Estonia and Bulgaria, had poor profiles for the percentage of small and large firms.

[7] Sensitivity: a combination of factors such as (i) species-level change in thermal habitat suitability, (ii) species-level production control, (iii) species-level knowledge and (iv) national-level aquaculture value

[8] Adaptive capacity: based on (i) firm structure/size, control measures identified and (iii) extent of national climate adaptation plan implementation

- **Exposure**[9] had the smallest effect on vulnerability, only really significant for Baltic Countries (esp. Finland and Estonia) where water temperatures were projected to warm enough to decrease the suitability of trout farming.

The results of this climate vulnerability analysis for European aquaculture suggests that **the direct effects of climate-driven warming (through 2050) will have limited, direct negative impacts on species currently cultured in most areas. Most of the vulnerability to Europe's aquaculture sector stems from effects that are either indirect or are related to differences in the adaptive capacity based on the method of cultivation.**

This said, Peck *et al* (2020), also part of the CERES project suggest that by 2050 the inland pond farming of species such as common carp will be significantly lower than that at present, with blue mussel and Pacific oyster productivity also falling. By 2100 sea bream farming in Spain will also be significantly less productive[10]. In contrast Irish salmon productivity will have increased.

As described by Kreiss *et al* (2020), again as part of the CERES project, climate-driven changes in aquatic environments have already started to affect the European aquaculture sector's most commercially important finfish and shellfish species. In France, mussel production has been affected by rising sea water temperatures, compounded by increasing spider crab predation, also linked to climate change. Italy has lost nearly one-fifth of its water supply from 1991 to 2020 compared to 1921 to 1950[11], and the current drought has had severe impacts on the River Po, with likely effects on the extensive clam culture in the estuarine / coastal lagoon system. Similarly drought has had a major impact on Romania's extensive pond-based cyprinid farming and increasing water temperatures could put their indigenous trout cultivation at risk (Eurofish, 2020).

Building on Payne *et al's* conclusions that impacts in EU aquaculture are more likely to be indirect than direct, the Horizon 2020-funded CERES project considered that the sector might be particularly sensitive to the future development of feed costs, returns and marketing options compared to future environmental change (e.g., warming) and recommend that future scenarios should include political, social, legal and economic dimensions alongside the anticipated changes in the aquatic environment, an idea supported by food shortages anticipated from recent events in Ukraine.

[9] Exposure: based on projections for temperature, salinity and water currents, plankton and nutrient levels over 2040-2059

[10] The impact of raising temperatures is especially concerning for seabream, which shows lower thermal tolerance than European sea bass and meagre, with meagre appearing the most resilient (Cascarano et al, 2021)

[11] https://www.forbes.com/sites/carlieporterfield/2022/07/13/italian-drought-puts-one-third-of-national-agriculture-production--like-tomatoes-and-olive-oil--at-risk/?sh=62453834c4c5

3.2 Current approaches to climate change adaptation in EU aquaculture

As discussed above, whilst the impacts of climate change are likely to be profound over the longer term, its direct impact on EU aquaculture production has been limited to date. As a result there has been only a low level of pre-emptive action to protect aquaculture from the effects of climate change. This said, this summer's drought and extreme air temperatures are a wakeup call and show the necessity for such planning at sector level.

Perhaps most of the current progress has been made at governance level. One example is the inclusion of climate change adaptation in the new strategic guidelines. This is particularly important, as these guidelines are driving two, interconnected initiatives:

1. **The preparation by Member States of multi-annual national plans (MANPs) for aquaculture.** Responding to the new guidelines, these MANPs include a strategic approach to adapting to, and mitigating the effects of, climate change over 2022 – 2030.
2. At the same time, **Member States are preparing their Operational Programmes for the new European Maritime, Fisheries and Aquaculture Fund (EMFAF) over 2021 - 2027**. This should be linked to the MANPs and provide details on how both industry and governance organisations can access EMFAF funding for climate change adaptation and mitigation measures.

Section 4 provides guidance on the mechanisms and measures that might be adopted for climate change adaptation by EU aquaculture.

3.3 Current approaches to climate change mitigation in EU aquaculture

MacLeod *et al* (2020) estimated that European aquaculture produced around 6.8 million tonnes of CO_2e in 2017, mainly from salmonid (78%) and bivalve (12%) farming. They also found that, comparing global averages, aquaculture has a much lower emissions intensity (EI) than ruminant meat and is similar to the main monogastric commodities (pig meat and broiler meat). Production of crop feed materials accounted for 39% of total aquaculture emissions, rising to 57% when emissions arising from fishmeal production, feed blending and transport are added. It is noted that EU aquaculture consumed just over a million tonnes of aquafeeds in 2021 (Alexander Döring , FEFAC, pers. comm., 25 October 2022).

The bulk of the non-feed emissions arise from the nitrification and denitrification of nitrogenous compounds in the aquatic system and energy use on the farm (primarily for pumping water, lighting and powering vehicles).

As suggested by Jones *et al* (2022) the greatest opportunities for high-volume reductions in greenhouse gas (GHG) emissions are likely to come from changes in upstream and downstream parts of the supply chain, both in terms of feed production and transport, as well as post-harvest product distribution. This is supported by an as yet unpublished report on the carbon footprint of Irish salmon aquaculture at farm gate that indicates that 29% global warming potential (GWP) is from feed production and 41% from feed transport to site.

Jones *et al* (2022) also consider how aquaculture can mitigate or counteract climate change. This includes (i) on-farm shift to low-emission energy sources and transport and (ii) increased use of polyculture or IMTA systems e.g. co-farming bivalves & shellfish or fed-finfish & seaweed &/or seaweed. Kim *et al* (2020) emphasis that (i) eating low on the food chain was comparable to vegan for GHG and water footprints and (ii) pond-raised aquatic animals were by far the 'bluest' water-intensive foods. Jones *et al* recognise the possible contribution of seaweed and bivalve farming to carbon sequestration but warns there is a low immediate likelihood of long-term carbon sequestration from these sub-sectors.

Section 4 overleaf provides guidance on the mechanisms and measures that might be adopted for climate change mitigation by EU aquaculture.

Box 3: Synthesis - Brief review of climate change and its potential impact on EU aquaculture

Short-term climate change impacts can cause loss of production from extreme events such as floods, increased risks of diseases, parasites and harmful algal blooms. Climate-driven changes in temperature, precipitation, ocean acidification, incidence and extent of hypoxia and sea level rise, amongst others, are also expected to have long-term impacts in the aquaculture sector at multiple scales.

A climate vulnerability assessment of European aquaculture conducted by CERES suggests that suggests that the direct effects of climate-driven warming (through 2050) will have little, direct negative impacts on species currently cultures in most areas. Most of the vulnerability to Europe's aquaculture sector stems from effects that are either indirect or are related to differences in the adaptive capacity based on the method of cultivation. This suggests that the sector might be particularly sensitive to the future development of feed costs, returns and marketing options compared to future environmental change.

There is limited evidence of climate change preparedness and adaption by EU aquaculture to date. However there are strong signs of preparation in the form of forecasting e.g. via CERES and ClimeFish and setting the governance framework through the new EU guidelines for the sustainable development of EU aquaculture and the Member State preparation of MANPs and EMFAF operation programmes to identify and fund climate change adaption and mitigation measures over the next 5 – 10 years.

4. Potential solutions to a more climate change resilient EU aquaculture sector

This section examines potential solutions for European aquaculture to both *adapt* to - and *mitigate* (see previous **Section 1.2** for further explanation on these two terms) - the impacts of climate change. It is divided into three main sections:

1. Production systems: covers primary aquaculture production from hatchery to harvest.
2. Supply chain: covers the wider supply chain, including feed production, post-harvest processing, distribution and final consumption.
3. Policy support: takes a broader look at how policy support could be developed at both EU and national levels.

4.1 Production systems

The EU aquaculture sector essentially consists of three major sub-sectors, with different histories and characteristics: (i) marine finfish (22% by volume); (ii) marine shellfish (54% by volume); and (iii) freshwater finfish farming (24% by volume). Crustaceans and seaweed are also farmed in the EU, but these activities have been developed on a smaller scale to date (Huntington, 2021).

- Marine finfish culture mainly takes place in open-water coastal pens (cages), although there is a trend towards both moving further offshore as well as moving onshore into flow-through and recirculated tank systems. The main species involved are salmon, sea bass, sea bream and meagre.
- Marine shellfish and seaweed culture includes off-bottom culture where the shellfish (e.g. mussels, oysters and clams) is elevated away from the bottom substrate by either plastic bags on steel trestle or on wooden 'bouchot' pole or is directly laid on the bottom substrate and is essentially grown without any *in situ* infrastructure and is harvested using traditional fishing gear (e.g. dredges). Shellfish are also reared on suspended ropes hanging below rafts and floating longlines. Most seaweeds (macroalgae) are also grown on long-lines and surface structures. Both shellfish and seaweeds have potential to be grown with finfish systems as part of an IMTA approach.
- Most land-based aquaculture uses tanks and raceways at some point in their production cycle, especially during the hatchery / nursery stages, but also for grow-out. Tanks and raceways are developed in a land-based controlled environment with varying levels of water conditioning (e.g. temperature) and recirculation. A more traditional approach to land-based farming takes place in earthen ponds, both flow-through (e.g. for trout) and static (e.g. for carp).

These systems vary in both *nature* (e.g. marine systems tend to be open-water e.g. finfish pens or off-bottom and on-bottom shellfish, whilst freshwater systems tend to be enclosed e.g. in tanks or raceways) and *scale* (e.g. pen culture tends to be large-scale, whilst shellfish and ponds farming is small-scale). However many of the *adaptation* and *mitigation* opportunities are common across these, so they are considered together. Where there may be certain issues or opportunities for different production segments, these are pointed out in the text.

4.1.1 Adaptation

Adaptation means altering and diversifying aquaculture systems to both (i) make them more resilient to the impacts of climate change and (ii) adapt to changes in the climate and associated conditions in order to maintain environmentally and economically sustainable aquaculture in Europe. Various approaches have been suggested, including:

Realigning existing production and diversifying into new, lower carbon species and systems: whilst climate change has the potential to impact current production patterns, its effects will also provide opportunities for 'realigning' traditional European aquaculture and stimulating an additional diversification into new, possibly lower-trophic species and IMTA systems. Key aspects of this include:

- Realign current 'mainstay' species and production systems: the current finfish and shellfish species being farmed in the EU will need to adapt to climate change. Whilst some of this will be approached through farm-level actions (see below) and policy level (e.g. via marine spatial planning, see **Section 4.3.1**), private sector investors and operators will need to forward-looking, especially over the medium to longer-terms. For instance *carp production* may benefit from a greater number of optimal production days, but these benefits may be offset by increased disease concerns and the risk of flooding in winter (Taylor *et al*, 2019). It is suggested that maintaining carp farming profitability in the face of climate change may require some restructuring (e.g. SME clustering, upscaling or vertical integration) as well as building resilience through increased levels of water recirculation and temperature control.

  For *marine finfish* like seabass and seabream, there are opportunities to increase profitability under different climate change scenarios. However despite the potential benefits in terms of growth associated with warmer temperatures, there are well founded stakeholder concerns relating to increased stock losses at higher temperatures due to reduced oxygen, increased stress and the occurrence of harmful algal blooms (HABs) and disease. The increasing incidence and severity of storms suggests that the development of robust new cage and culture systems that can tolerate harsh sea states and offshore conditions are needed.

  CERES suggested that climate change may make *blue mussel farming* in the Netherlands unviable yet may improve profitability in Danish waters (Taylor, 2019). Overall there will be a need to change business models[12] and move culture into cooler, possibly offshore waters.

- Diversify into less-used, lower-trophic species: as noted by Taylor *et al* (2019) shellfish, seaweed and other lower-trophic taxa will be key to the success of European aquaculture moving forwards. Whilst bivalves such as mussels, oysters and clams are already commonly farmed in Europe, other *shellfish species* such as clams and warm-water prawns may have potential niches in European aquaculture. *Seaweed* (macroalgae) is also much advocated due to its carbon sequestering and bioremediation abilities, rapid growth and potential array of food and non-food products. Less-used *finfish species* such as meagre and greater amberjack may provide opportunities for filling emerging niches in marine warm-water cage culture, and grey mullet for warm-water pond, extensive and integrated culture, and pikeperch for freshwater intensive

[12] it is likely that business models will need to move towards larger companies or co-operatives that manage multiple sites and can allow cost sharing between sites so that equipment and staff costs can be reduced (Taylor *et al*, 2019)

culture using RAS (see http://www.diversifyfish.eu/species.html) as well as tilapia in ponds and tanks, especially with higher water temperatures.

- Integrate multi-trophic aquaculture: IMTA has long been advocated as an approach for more efficient and ecologically sustainable aquaculture. Typical systems combine marine finfish pens with shellfish and seaweed but can also be in the form of freshwater IMTA processes relying on a naturally occurring microalgae, bacteria and aquatic plants such as duckweed in ponds to manage waste and water quality (O'Neill *et al*, 2022). IMTA also includes hydroponic aquaculture integrating animal, fish and plant production in urban settings.

Adapting and modifying on-farm management and husbandry: In addition to the medium-long-term adaptation processes suggested above, shorter-term adaptation to the already present effects of climate change can also be made at farm level. Key aspects of this include:

- Improved farm management and husbandry: many of the impacts of climate change – increased water temperatures and extremes in water supply (e.g. droughts and flooding) – can be managed to a certain extent at farm level. Aeration or oxygenation may allow stocking densities to be maintained at higher temperature extremes[13]. Related to this, more tailored feeding regimes will help control post-prandial oxygen demand whilst reducing the chemical and biological oxygen demands from unused feed and faeces.
- More controlled growing environments: whilst improved aeration and feeding may help in the case of minor climate change impacts, more extreme impacts may require technical and infrastructural changes to the growing environment. For instance with both the aforementioned changes in water temperature and water availability, increased levels of recirculation may be needed to maintain optimal water temperatures, reduce the demand for external water inputs and allow greater control of water quality. However, this is likely to be energy intensive and will increase investment and running costs in the investment in infrastructure required by these sites will be prohibitive to most small producers, unless supported by solar power and battery storage systems.

Building resilience into aquaculture production: whilst the previous text focused on farm-level husbandry, resilience to climate change induced effects can be built up through more strategic thinking by farm operators into aspects such as building stock resilience to climate change induced environmental and biosecurity challenges:

- More resilient stock via selective breeding: selective breeding may assist in providing better survival and growth under more variable and potentially stressful environmental conditions than generic strains. For example the so-called BORN strain of rainbow trout produced in the northeast of Germany that have demonstrated a generally elevated resistance towards high stress and pathogenic challenge including lower susceptibility towards *Aeromonas salmonicida* infections in comparison to other trout strains (Rebl, 2012).
- Improved and adaptive biosecurity: the incidence, nature and virulence of fish disease is closely linked to temperature regime and environmental stress (amongst other factors), and thus climate change is likely to have a strong influence on this, as well as the incidence of mortality-inducing events such as HABs. So as well as the farm and stock-level resilience-building measures discussed above, approaches to better monitor stock health and pathogen levels, as well as to

[13] Warmer water holds less oxygen and fish often have higher metabolism and therefore oxygen demand.

ensure biosecurity at farm, intra-farm and transboundary levels may be required (Cascarano *et al*, 2021). HAB prediction modelling and monitoring may also need to be developed, as these types of events become more common. Over the longer-term, the emergence of new, possibly zoonotic diseases needs to be anticipated and responded to.

Informed decision-making at farm level: this section looks at how farmers might be better-informed in order to make evidence-based decisions on short, medium and long-term management and planning to adapt to the impact of climate change.

- Improved on-farm environmental and performance monitoring systems: the already established use of on-farm environmental and stock monitoring systems could be expanded to complement the measures advocated above. For instance, dissolved oxygen, carbon dioxide, pH and temperature are all critical indicators environmental health and stress (Cascarano *et al*, 2021).
- Use of decision-support systems: one approach advocated by the ClimeFish project is the use of decision-support systems (DSSs) to model the profitability associated with different stocking strategies, harvest sizes, farm sizes and location on different climate and husbandry scenarios (Stavrakidis-Zachou *et al*, 2018; Stavrakidis-Zachou *et al*, 2021). Such models will benefit from the increased availability of environmental and performance data discussed above.

As stressed by stakeholders consulted as part of this study, over the short-term there is a particular need to enable EU aquaculture producers to anticipate – and respond to – the growing frequency of climate-change related impacts, such as unusually high water temperatures, water quality problems and issues associated with increased predation and other stock threats. The likely solutions will reflect the environmental monitoring and decision-support models mentioned above, but bespoke solutions will need to be developed for particular bio-geographic and production sector related situations, for instance northern French shellfish production in the Channel.

4.1.2 Mitigation

Climate change mitigation means avoiding and reducing aquaculture's contribution of emissions of heat-trapping greenhouse gases e.g. from animal respiration, refrigeration and transportation. Life cycle analysis (LCAs) of salmon farming have shown that whilst the majority of the global warming potential (GWP) of intensive finfish farming comes from the food component (see **Section 4.2**), energy use over the land-based juvenile production (e.g. for heating/treating water, together with running pumps), as well as for the sea-based grow-out stage (e.g. for feeding and sea transport) is considerable (Winter *et al*, 2020).

Two possible approaches to mitigate these exist:

- Alternative, low carbon energy sourcing and efficiency improvement: with the current global energy crisis, there is considerable effort to reduce energy use and associated costs. There are extensive options including the use of renewable energy on site (e.g. solar, wind and possibly tidal) supported by ever-improving battery storage solutions, move to hybrid-powered well and support vessels. LCAs and carbon footprint modelling can also introduce carbon footprint elements in decision-making e.g. comparing the GWP costs of different land and sea-based systems. For instance the 'super smolt' concept of holding salmon juveniles longer in land-based tank systems may have unanticipated GWP costs, as such systems often have a high electricity demand for pumps, filtration and water temperature control.

- Diversification of products from European aquaculture: some aquaculture products may have the potential to offset or replace traditional higher GWP outputs. The obvious example is macroalgae that has limited food value on human markets but could be used in animal feeds, fertilisers, cosmetic products, bioplastics and possibly even biofuels. However this has to be undertaken with some care, as large-scale seaweed production has potential co-existence and environmental issues (e.g. shading and altering local productivity). There may also be opportunities to sequester carbon in bivalve shells (Moore, 2020).

4.2 Supply chain

Whilst much can be done at farm-level, the aquaculture supply chain will also need to adapt to the impacts of climate change. There is also has considerable potential to reduce or mitigate the GWP potential of the supply chain - in particular in regard to aquafeed production – as well as encouraging and enabling consumers to choose lower-carbon aquaculture products as part of the overall transition to carbon neutrality in the EU.

4.2.1 Adaptation

There is no doubt that the European aquaculture supply chain will need to adapt to the impacts of climate change. This is wide-ranging and much of which is outside the scope of this study e.g. how wild fisheries and land-based agriculture producing aquafeed ingredients will need to adapt to changing marine and terrestrial environmental conditions. However we will briefly focus on two opportunities, (i) the use of alternative, low carbon raw materials and (ii) encouraging consumer interest in low-carbon aquaculture products.

- Alternative low GWP aquafeed raw materials: most aquafeeds, especially for higher trophic levels species such as salmonids, sea bass, sea bream and meagre, contain high level of protein derived from both animal and increasingly, plant-based sources. The increased use of LCAs (e.g. including PEFs) are allowing decision-makers to factor in carbon footprint considerations to other commercial factors when purchasing raw materials. There is also increasing interest in circular feed materials such as black solder fly meals, as well as improved recycling of processed animal proteins from rendering plant facilities, such as feather meal (Ghamkhar & Hicks, 2020).
- Changes in consumption: Kim *et al* (2020) emphasis that shifts towards 'plant-forward' diets comprised of plant foods with modest amounts of low trophic level animals (i.e., forage fish, bivalve molluscs, insects) with comparably small GHG and water footprints would have a combination of net-zero, health and resource benefits. This suggests that encouraging and enabling consumers to increase the contribution of these lower-trophic alternatives as part of a balanced diet could have considerable cumulative advantages (Ghamkhar *et al*, 2021). This will need to be implemented through a range of approaches, including product development as well as consumer information provision. The Danish Ministry of Food, Agriculture, and Fisheries has recently announced their funding the development of a 'climate label' for food, making Denmark the first EU country to do so[14].

[14] https://www.dailyscandinavian.com/voluntary-climate-labelling-in-denmark/

4.2.2 Mitigation

The greatest opportunities for high-volume reductions in GHG emissions are likely to come from changes in *upstream* (e.g. inputs into aquaculture, such as feeds and materials) and *downstream* (e.g. post-harvest) parts of the supply chain, both in terms of feed production and transport, as well as post-harvest product distribution. This is supported by an as yet unpublished report on the carbon footprint of Irish salmon aquaculture at farm gate that indicates that 29% global warming potential (GWP) is from feed production and 41% from feed transport to site.

The seafood trade involves a huge amount of material transportation, both in terms of aquafeeds to site as well as the post-harvest distribution of seafood products to processors and markets. Supply chains are efficient but mainly consider fuel / logistic costs rather than GWP. The monetary cost of climate change therefore needs to be considered as part of the overall cost of doing business. To put some perspective on this, one study (Yumashev *et al*, 2019) considers that the economic cost of climate change under the 1.5 °C target would be USD 638 trillion. Furthermore the cost of largely unchecked climate change — the 'business-as-usual' trajectory leading to a 4°C temperature rise — is around USD 2,000 trillion, suggesting forward investment is critical.

As discussed above, LCA and PEF modelling can assist identify where GWP reduction gains can be made and how these can be factored into wider commercial decision-making. This might include the following aspects of the aquaculture supply chain:

- Aquafeed production and sourcing. For instance it may allow a case to be made for local aquafeed production, even if this is marginal purely on economic terms.
- Increasing local post-harvest processing and value-adding. In the past some European seafood companies send whole fish to Asia for filleting and other processing to take advantage low labour costs. Regional or local processing (e.g. filleting) can reduce product volumes, thus reducing subsequent refrigeration and transport-related emissions.
- Other circular approaches. A responsible, circular approach by aquaculture companies can reduce raw material costs and wastage. For instance the improved decommissioning and recycling of pen collars and other large and single use plastic components could have substantial gains in both GWP and other environmental terms[15].

[15] Sundt *et al* in 2014 estimated that 11 kg of plastic waste is generated for every tonne of aquaculture product output in Norway. More recently, Sundt (2018) estimates that in Norway 25,000 tonnes of plastic from aquaculture is discarded at sea annually (e.g. net pen collars, pipes, nets, feed hoses and ropes).

4.3 Policy support

This section focuses on how policy support could be developed at both EU and national levels to both help aquaculture adapt to climate change and to mitigate its own impacts.

4.3.1 Adaptation

The EU's policy framework (see **Section 2**) for sustainable development of EU aquaculture is based around a number of sector-specify and wider initiatives. These opportunities are briefly explored below.

- Climate Change Action planning: the new strategic guidelines for a more sustainable and competitive EU aquaculture (2021 to 2030) emphasise the need for Member States to develop aquaculture climate adaptation plans (aCAPs) consistent with national strategies and plans, as well as the corresponding European Committee for Standardization (CEN) standard. Pham *et al* (2021) recently developed guidelines for co-creating aCAPs for aquaculture, including a three-step process of: (i) assessment of risks and opportunities; (ii) identifying adaptation measures and (iii) implementing the aCAPs.
- Support adaptation via EMFAF and other relevant public funding: with the new Member State multi-annual national plans (MANPs) for aquaculture and Operational Programmes for funding support through the EMFAF, there is an opportunity to facilitate climate change adaptation (and mitigation) through targeted measures, training and awareness-raising. Other funds, such as Horizon Europe, can also be leveraged for research and innovation. There are also as co-funding opportunities for promoting the ecosystem services from aquaculture e.g. in carbon capture and sequestration (AAC, 2021). It is noted that SMEs should not be unnecessarily excluded from these opportunities
- Role of marine spatial planning in helping aquaculture adapt to climate change: it is important that marine spatial planning (MSP) is forward-looking and assists EU aquaculture adapt to climate change over the medium to long-term. This can include examining how site selection might change e.g. the movement of both finfish and shellfish farming to deeper, cooler waters, as well as maximising co-existence opportunities between both different forms of aquaculture (e.g. IMTA) and with other maritime economic activities, such as offshore wind farming.

4.3.2 Mitigation

The main policy approach to mitigating the contribution of EU aquaculture to climate change will be through the wider policy drive to a climate-neutral EU by 2050 and decarbonisation of the energy sector. In particular this might mean investment in the transition process, especially towards assisting aquaculture practitioners – and the wider value chain – to reduce over-all energy used and their dependence upon fossil fuels.

Box 4: Synthesis - Potential solutions to a more climate change resilient EU aquaculture sector

Although climate change has the potential to impact current EU aquaculture production patterns, its effects will also provide opportunities for 'realigning' the geography and nature of current European aquaculture and stimulating a diversification into new, possibly lower-trophic species and IMTA systems. There are also potential on-farm solutions to adapting to more variable or extreme environmental conditions, as well as wider solutions for building resilience into aquaculture, for instance through selective breeding and better biosecurity.

In terms of climate change mitigation, research shows that the greatest opportunities for high-volume reductions in greenhouse gas (GHG) emissions are likely to come from changes in upstream and downstream parts of the supply chain. In particular, the use of lower carbon raw materials for aquafeed will be key. LCA approaches like Product Environmental Footprint analysis will also allow the mitigation intervention points over the whole value chain to be identified. This will in turn allow carbon-related costs to added to conventional commercial factors for decision-making, both for operators as well as Member State sustainable aquaculture sector development planning.

5. Resilience of EU aquaculture compared to terrestrial food production systems

This section will first build on the previous text to provide an opinion on how resilient EU aquaculture is to climate change and provides an upbeat vision of how a progressive, low-carbon aquaculture sector might look like in 2050. We then look at the plans for making terrestrial agriculture more resilient to climate change in Europe and the possible lessons for the aquaculture sector.

5.1 How resilient is EU aquaculture to climate change?

The key message is that once the sector recognises the need for change from the current *status quo*, the shift towards a more resilient and lower carbon aquaculture sector will bring many opportunities as environmental gradients move in response to climate change. Research conducted for the CERES and ClimeFish projects suggest that whilst there will be winners and losers from these changes, EU aquaculture production has the ability to both adapt to these changes and to remain resilient to its evolving indirect impacts e.g. disease and other issues often related to environmental stress.

This said, there are considerable challenges ahead. The extremely dry summer of 2022 has demonstrated the vulnerability of land-based aquaculture to water shortages and perversely the flash floods that follow. Marine aquaculture is not immune - the recent post-drought heavy rainfall along the south coast of England has resulted in higher storm-water discharges and accompanying sewage contamination that has the potential to even affect offshore shellfish aquaculture systems. There are also a number of emerging and potentially highly disruptive issues associated with climate change such as ocean acidification that suggests diversification from the existing limited species diversity in EU shellfish aquaculture will be key to its continuation (Sinclair-Stewart *et al*, 2020).

If we were to peer into the future and to how a progressive, low-carbon EU aquaculture might look like in 2050, it might appear something like this:

- Realignment of traditional aquaculture species (e.g. salmon, trout, sea bass, sea bream, blue mussels and oyster) production to reflect changing thermoclines and other environmental factors. This will be accompanied with a movement further offshore for marine aquaculture, facilitated by forward-looking marine spatial planning.
- A move away from current open-water systems with greater degree of containment and system environmental management e.g. partial and fully-enclosed pen systems. This will improve efficiency and reduce vulnerability to external issues such as HABs.
- Increased use of partial or full RAS as expertise is gained and electricity costs drop after 2025 as the EU energy market stabilises[16] with a greater contribution of solar and wind power by 2050 (see **Figure 7** in **Appendix B**).
- Increased use of resilient, high performing fin and shellfish stock lines with a gradual move towards new genetic selection approaches that have been thoroughly impact assessed.

[16] See https://blog.energybrainpool.com/en/eu-energy-outlook-2050-how-will-the-european-electricity-market-develop-over-the-next-30-years/

- The use of remote environmental monitoring systems, combined with artificial intelligence (AI), that predicts and manages aquaculture system management to maximise growth and survival as well as minimise energy and material inputs into the system.
- Risk management will become mainstreamed into aquaculture planning and reflected in the widespread uptake of robust and affordable insurance schemes.
- Diversification into new and less-used species, with a tendency towards lower-trophic animals and plants. This will allow emerging environmental niches to be occupied (e.g. tilapia in warmer ponds), large-scale carbon sequestration and remediation (e.g. via seaweeds) and efficient in-combination systems through IMTA and polyculture.
- Aquafeeds are prepared from locally-available, low trophic materials such as insect protein, single-cell protein and algae protein.
- Regional aquafeed production hubs utilising locally-sourced materials.
- Rationalisation of businesses with greater cooperation and possible clustering of aquaculture SMEs as well as greater levels of vertical integration across and between businesses.
- The aquaculture supply chain generating and storing its own electricity from a variety of on-site renewable sources, supplemented by mains grid electricity from large-scale renewables and low-carbon generation.
- All marine / land transport powered by electric or hybrid-electric propulsion units.
- The carbon footprint of aquaculture products is a key consideration by consumers in making food choices, supported by decision-support tools such as PEF and third-party certification.

5.2 Review of the resilience of EU terrestrial food systems to climate change

Climate change affects European agriculture and requires agricultural systems and farmers to adapt. Rising temperatures and atmospheric CO_2 concentration, changes in precipitation patterns and more frequent extreme events influence crop yields and livestock productivity in Europe, but also water management and conditions for transport and storage. Crop productivity is expected to generally decrease in Southern regions and to increase in the North, while more frequent extreme weather events will cause scattered and detrimental impacts all across Europe (**see Box 5: Summary of climate change impacts to EU agriculture up to 2050** overleaf).

In turn the agricultural sector is one of the main drivers of climate change, emitting methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) mainly related to land use, fertiliser application and livestock production. The share of agriculture in European GHG emissions is currently around 11%.

Box 5: Summary of climate change impacts to EU agriculture up to 2050

The JRC's PESETA IV project analysed climate change projections for 2050 for global warming levels ranging between 1.6° C and 2.7° C (compared to pre-industrial levels) as well as for 1.5 °C and 2° C warming conditions. Their results show that climate change will pose a threat to global food production in the medium to long term and that Europe will also be affected. Forced by the projected changes in daily temperature, precipitation, wind, relative humidity, and global radiation, grain maize yields in the EU will decline between 1% and 22%. In addition, wheat yields in Southern Europe are expected to decrease by up to 49%. However, in Northern Europe some of the negative productivity effects caused by climate change may be partially offset by higher levels of atmospheric CO_2 concentrations and changing precipitation regimes.

Losses, especially in Southern Europe may be reduced by tailored adaptation strategies; e.g. changing varieties and crop types, increasing and improving irrigation practices for certain crops and when economically feasible. However, limitations on sustainable water abstraction levels could become a barrier to increase irrigation levels, specifically in the Mediterranean countries (particularly Spain, Portugal, Greece, Cyprus, Malta, Italy and Turkey) where duration of water scarcity under global warming are projected to intensify.

As large negative climate change impacts on productivity outside of the EU are estimated, large market spill-over effects will push up production in both Northern and Southern Europe through higher demand for some agricultural commodities outside of EU, resulting in higher producer prices. This, in turn, may benefit farmers' income and have positive effects on the EU's agricultural commodity exports.

It was noted that, due to a lack of quantitative data and models availability, in this study livestock commodities were assumed to be not directly affected by climate change (e.g. increasing temperature, higher flood risk), but indirectly through the effects on feed prices and trade, which are transmitted to dairy and meat production. In reality, certain temperature increases due to climate change may severely threaten livestock productivity, especially if adaptation strategies are not put in place.

Source: Hristov *et al.*, 2020

There are a number of adaptation measures available at various spatial scales for adapting crop, livestock, viniculture and horticulture production to climate change, with various benefits for mitigation, soil quality and biodiversity. Similar to aquaculture, these can be conducted at both national or regional levels, as well as farm level.

National or regional level adaptation measures are likely to include:

- Integrating adaptation into farm advice
- Risk management insurance against weather and climate
- Improving efficiency of irrigation infrastructure
- Flood management and prevention

Many adaptation measures at the *farm level* are largely extensions of existing climate risk management or measures to enhance production in response to a potential change in the climate risk profile (see **Figure 8** in **Appendix B**). In the future, the need for risk management tools will probably increase because of the greater frequency and magnitude of extreme events.

In terms of policy responses, the EU *Strategy on Adaptation to Climate Change* (2021) aims to make adaptation smarter, faster and more systemic (EEA, 2020). Stimulating local adaptation, nature-based solutions, sustainable uses and resilience of fresh water resources are particularly relevant for the agricultural sector, whereas stepping up international action is essential to avoid disruption of EU agricultural imports.

The proposals for adaptation of the *Land use, land use change and forestry (LULUCF) Regulation*[17] aim for increased carbon capture in agriculture and forestry, with important land cover change implications. The measures to achieve this, such as maintenance of grasslands, carbon farming and restoration of peatlands, will also help preventing soil erosion and reducing flooding risk.

Concrete adaptation measures in the agricultural sector are primarily supported through the *Common Agriculture Policy* (CAP), with sustainability and climate action as core objectives. Dedicated adaptation measures have not played a prominent role in the CAP until now, but the obligatory and voluntary greening measures often provide short to medium term adaptive solutions at farm level. A green payment under CAP Pillar 1 covers crop diversification, establishment of ecological focus areas and maintenance of permanent grassland. Rural development support under CAP Pillar 2 includes forest development, agri-environment-climate measures, organic farming, and Natura 2000 payments. The funding schemes are supplemented with training measures and other support to improve productivity and resilience to climate change from the Farm Advisory System, the Innovation Partnership and applied research.

In line with the European Green Deal, the Farm to Fork Strategy, the Biodiversity Strategy, the CAP proposals for 2023-2027 put more emphasis on environmental and climate action. Strengthened obligatory measures and more funding opportunities are established for the preservation of carbon-rich soils, crop rotation, nutrient management and eco-schemes.

[17]The Land Use, Land Use Change and Forestry (LULUCF) (Regulation (EU) 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 Climate and Energy Framework

5.3 Comparative analysis of how aquatic and terrestrial farming systems will adapt to the impacts of climate change

It is evident that in both aquaculture and agriculture there will be winners and losers from climate change. This said, it is apparent that land-based agricultural cropping systems will be more vulnerable to the impacts of climate change, mainly due to the heavy dependence upon predictable rainfall patterns and supporting irrigation systems. In comparison, the buffering effect of large volumes of sea water will provide marine aquaculture some leeway in adapting to sea water temperature rise.

As discussed earlier, the CERES project suggests that the main impacts of climate change in aquaculture will come through indirect routes, such as the future development of feed costs, returns and marketing options compared to future environmental change. It is likely that terrestrial livestock farming will also be relatively unaffected by climate change, with similar indirect impacts from feed inputs. This said land-based aquaculture, especially traditional extensive pond farms, will need to adapt to both the increased competition for water as well as the increasing incidence of sudden catastrophic events such as flooding and storm damage.

In terms of commonalities between aquatic and land-based food production, there are two key messages:

- **Informed consumer choice** could have a major impact on both production systems. EU meat consumption is set to decline from 69.8 kg in 2018 to 67 kg retail weight per capita by 2031, contrary to the trend at world level. In particular beef is expected to continue its declining trend, being replaced mainly by poultry (EC, 2021e). Likewise a shift towards 'plant-forward' diets comprised of plant foods with modest amounts of low trophic level seafood (i.e., forage fish, bivalve molluscs, seaweed products) with comparably small GHG and water footprints would have a combination of net-zero, health and resource benefits. This suggests that efforts to enable consumers to make informed choices on low-carbon food options, such as PEF and other analyses, will be well rewarded.
- **Although much of the transition will be led by market forces, both the EU and Member State governments have an important role in laying the foundations for resilient and carbon-neutral food production in the EU**. In particular the new CAP is strongly allied to the European Green Deal and climate change adaption / mitigation. This will ensure that funding opportunities will be increasingly focused on supporting Member States in developing and implementing measures to increase climate change resilience and to reduce the substantial (*c.* 11%) contribution of agriculture to EU GHG emissions. Likewise the EMFAF with – through Member State MANPs and EMFAF Operational Programmes – identify and target measures to ensure a more resilient aquaculture sector whilst reducing its own, albeit smaller contribution to EU GHG emissions.

In summary, there has been a major movement by the EU to recognise the vulnerabilities of food production to the impacts of climate change and, through projects such as CERES and ClimeFish, to assess routes to greater food security and lower associated carbon emissions. With the necessary planning and funding mechanisms now largely in place, it is up to Member States - both in terms of the public and private sectors – to ensure this ambition is realised.

Box 6: Synthesis - Resilience of EU aquaculture compared to terrestrial food production systems

Despite some particular vulnerabilities, both aquatic and terrestrial livestock production are relatively resilient to the impacts of climate change, especially when compared to plant-based agriculture. Indeed, as has been well documented, their similar dependence upon high protein feeds mainly of terrestrial origin, is a common indirect vulnerability. Crop farming, as well as some land-based aquaculture, is more vulnerable largely due to their dependence upon ample and stable water supplies. This is likely to lead to considerable changes in crop agriculture patterns in southern Europe over the next few decades.

In terms of mitigating the EUs contribution to GHG emissions, moving some aquatic and most terrestrial livestock production to a lower carbon approach is vital as they are disproportionately high GHG emitters, due to their dependence upon high protein feeds and the metabolic characteristics of the livestock species involved (e.g. salmonids, sea bass and sea bream in aquatic systems and beef, pigs and poultry in terrestrial systems). This said, the emissions intensity of most finfish lies between 4 and 6 kg CO_{2}-e/kg carcass weight (cw) whilst beef is over 40 CO_{2}-e/kg cw and sheep 30 CO_{2}-e/kg cw (MacLeod *et al*, 2020), so the onus will be on the terrestrial livestock industry to respond accordingly.

Consumers will have an important role in shaping market forces towards lower-carbon food production. Therefore efforts to ensure they are informed of the full carbon footprint of different food choices will be essential.

Finally we consider that the wider EU policy framework to move towards carbon-neutrality by 2050 is now in place, together with the strategic planning and funding mechanisms to support this transition. It is now up to it is up to the Member States - both in terms of the public and private sectors – to ensure this ambition is realised.

6. Recommendations

This final section provides some brief recommendations to support Europe's transition to a climate change-resilient and low carbon aquaculture sector. This is intended to complement the EU's guidelines for sustainable aquaculture development (2021 to 2030) as well as future AAC activities in this area, in particular the planned 'Climate change impacts on aquaculture activities in Europe' activity under Working Group 3 (WG 3) in 2022 / 2023.

6.1 EU and Member State level

1. Support Member States to link climate change-related strategies in their MANPs to their EMFAF Operational Programmes, associated measures and actions. At strategic level this might include conducting national aquaculture carbon footprint analyses in order to identify strategic options for reducing the GWP of aquaculture, e.g. through supporting (i) more circular and low-carbon aquafeed production or (ii) shorter processing and value-adding chains / routes.
2. Related to the point above, include monitoring indicators to assist the evaluation of EMFAF-funded climate change-related actions in Member State data collection. This process could be supported via FAMENET (Fisheries and Aquaculture Monitoring, Evaluation and Local Support Network).
3. Consider the possibility to conduct life cycle analyses, including the inclusion of Product Environmental Footprint (PEF) assessments across all EU aquaculture operations. Given the strong SME contribution, cumulative or group assessments might be considered for smaller operations.
4. Related to the point above, develop metrics to evaluate progress in climate change mitigation by the EU aquaculture sector. This could be linked to specific EMFAF (and its successor) support.
5. Specific guidance through the Open Method of Coordination (OMC) for aquaculture or other mechanisms (e.g. the EU's new Aquaculture Technical Assistance Platform) on studies that fill information gaps or support climate change adaptation and mitigation. These might include:
    a. Practical decision-making tools for aquaculture SMEs to adapt their operations to the short and longer-term impacts of climate change.
    b. Develop rapid impact forecasting and impact assessment methodologies for key bio-geographic areas / production systems to help businesses anticipate and respond to short-term, often seasonal extreme events and environmental perturbations.
    c. How climate change-induced environmental change might impact social, economic and legal systems and how these can be mitigated.
    d. Mechanisms for including climate change adaptation and mitigation into MSPs and their updates (see next).
6. MSPs and their updates should include the spatial management for more resilient systems e.g. offshore or semi-contained pens, as well as promoting IMTA and coexistence with other maritime economic activities.
7. Cross-EU research e.g. via Horizon Europe on new technologies to build resilience e.g. finfish and shellfish strains that perform well under more extreme environmental conditions, less-used species that can fill new niches under different climate change scenarios,

8. Promoting the development of aquaculture clusters, associations and other collective mechanisms that provide greater commercial resilience to the impacts of climate change on individual operators and other SMEs.
9. Support Member States develop aquaculture climate adaptation plans (aCAPs) consistent with national strategies and plans, as well as the corresponding European Committee for Standardization (CEN) standard.

6.2 Industry level

1. EU aquaculture equipment manufacturers, together with progressive farmers, should be proactive in working with research bodies to design and pilot test more resilient aquaculture systems and strategies e.g. robust offshore finfish, shellfish and macroalgae growing systems, increased control of environmental conditions through containment, the use of AI in environmental management, etc.
2. Larger farms conduct carbon footprint 'audits' through PEF or other LCA approaches and evaluate what measures can be taken to reduce their GWP over the shorter-term, as well as planning their business GWP over the longer-term.
3. Ensure that carbon footprint considerations are included in procurement decisions, especially for aquafeeds and other potentially high carbon inputs. Where possible source low-carbon alternatives, and facilitate the circular management of farm waste, both biological and non-biological.
4. Third-party aquaculture environmental certification schemes include carbon management in their sustainability performance metrics.
5. Increased uptake of (i) environmental monitoring systems that support good husbandry practices and (ii) decision-support tools such as those developed under ClimeFish that allow better business planning in the face of climate change over both the short and longer terms.
6. Conduct cost-benefit analyses to support the investment into low carbon energy sourcing at farm level. This could include solar (photo-voltaic) and wind energy production at sea and on shore bases with associated battery storage. It should also include investment in electric vehicles and electric / hybrid marine propulsion systems.
7. Development of new seafood products that utilise low-trophic plants and animals to help move seafood consumption away from the current focus on carnivorous species such as salmon, trout, sea bass and sea bream.

Appendix A: References and Bibliography

AAC (2021). The provision of ecosystem services by European aquaculture. June 2021 - (AAC 2021-08). 39 pp.

Anon (2022). Product Environmental Footprint Category Rules (PEFCR) for unprocessed Marine Fish Products. Version: Draft v5 for Supporting Studies; Version date: 06.09.2022. 57 pp. Downloaded from https://www.marinefishpefcr.eu/_files/ugd/2c010a_b6e0bc4fecf349d2826cf30892e37f7c.pdf on 24 October 2022.

Barange, M., T. Bahri, M. Beveridge, K. Cochrane, S. Funge-Smith & F. Poulain, eds. (2018). Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. *FAO Fisheries and Aquaculture Technical Paper* No. 627. Rome, FAO. 628 pp. https://www.fao.org/3/i9705en/i9705en.pdf

BSI (2012). Carbon footprint for seafood – Product category rules (CFP-PCR) for finfish. . ICS code: 13.020.40. 37 pp.

BSI (2020). Assessment of life cycle greenhouse gas emissions. Supplementary requirements for the application of PAS 2050:2011 to seafood and other aquatic food products. BS ISO 22948:2020. 36 pp.

Cascarano, M, O. Stavrakidis-Zachou, I. Mladineo, K. Thompson, N. Papandroulakis & P. Katharios (2021). Mediterranean Aquaculture in a Changing Climate: Temperature Effects on Pathogens and Diseases of Three Farmed Fish Species. *Pathogens* 2021, 10, 1205. https://doi.org/10.3390/pathogens10091205

Cochrane, K.; De Young, C.; Soto, D.; Bahri, T. (eds) (2009). Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. *FAO Fisheries and Aquaculture Technical Paper.* No. 530. Rome, FAO. 2009. 212 pp.

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 2020*, 482–520. https://dspace.stir.ac.uk/retrieve/935c2493-94f2-48c6-b7a6-870f35dd39c0/21_aquaculture_2020.pdf

Energy Brainpool (2021). https://blog.energybrainpool.com/en/update-eu-energy-outlook-2050-how-will-europe-evolve-over-the-next-30-years/

entso-e (2021). https://tyndp.entsoe.eu/

EUMOFA (2021). The EU Fish Market. Highlights the EU in the world market supply consumption import – export landings in the EU aquaculture. 2021 edition. Directorate-General for Maritime Affairs and Fisheries, B-1049 Brussels. 105 pp.

Eurofish (2020). Romania: Science-based measures to support those affected by climate change - Sustainable fishing and innovation can ameliorate impacts. *Eurofish Magazine* 6/20, 40-42.

European Commission (2013). Communication from the European Commission on the Strategic Guidelines for the sustainable development of EU aquaculture; 29.04.2013; COM(2013) 229 final. 12 pp. https://ec.europa.eu/fisheries/sites/fisheries/files/docs/body/com_2013_229_en.pdf

European Commission (2016). Energy, transport and GHG emissions – Trends to 2026. EU Reference Scenario https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

European Commission (2019). The European Green Deal. Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions. Brussels, 11.12.2019. COM(2019) 640 final. 24 pp. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

European Commission (2020). EU Biodiversity Strategy for 2030 - Bringing nature back into our lives. Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions. Brussels, 20.5.2020. COM(2020) 380 final. 22 pp + appendices. https://eur-lex.europa.eu/resource.html?uri=cellar:a3c806a6-9ab3-11ea-9d2d-01aa75ed71a1.0001.02/DOC_1&format=PDF

European Commission (2021a). 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 {SEC(2021) 89 final} - {SWD(2021) 25 final} - {SWD(2021) 26 final. Brussels, 24.2.2021 COM(2021) 82 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN

European Commission (2021b). Communication from The Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an Action Plan for the Development of Organic Production. {SWD(2021) 65 final}. Brussels, 19.4.2021. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0141R(01)&from=EN

European Commission (2021c). Communication from The Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on a new approach for a sustainable blue economy in the EU. Transforming the EU's Blue Economy for a Sustainable Future. Brussels, 17.5.2021,COM(2021) 240 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:240:FIN

European Commission (2021d). Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030. Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions. Brussels, 12.5.2021. COM(2021) 236 final. 17 pp + annexes. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:236:FIN

European Commission (2021e). EU agricultural outlook for markets, income and environment, 2021-2031. European Commission, DG Agriculture and Rural Development, Brussels. 60 pp +annex https://op.europa.eu/en/publication-detail/-/publication/c1f81e5e-74ec-11ec-9136-01aa75ed71a1/language-en

European Environment Agency (2019). Climate change adaptation in the agriculture sector in Europe. EEA Report No 04/2019. 108 pp. https://www.eea.europa.eu/publications/cc-adaptation-agriculture

European Union (2020). Farm to Fork Strategy. 20 pp + appendices. https://ec.europa.eu/food/sites/food/files/safety/docs/f2f_action-plan_2020_strategy-info_en.pdf

Ghamkhar, R., & A. Hicks (2020). Comparative environmental impact assessment of aquafeed production: Sustainability implications of forage fish meal and oil free diets. *Resources, Conservation & Recycling* 161 (2020) 104849. https://doi.org/10.1016/j.resconrec.2020.104849

Ghamkhar, R., S. Boxman, K. Main, Q. Zhang, M. Trotz & A. Hicks (2021). Life cycle assessment of aquaculture systems: Does burden shifting occur with an increase in production intensity? *Aquacultural Engineering* 92 (2021) 102130

Holmyard, N. (2014). Climate Change: Implications for Fisheries & Aquaculture. Key Findings from the Intergovernmental Panel on Climate Change (IPCC). Fifth Assessment Report. University of Cambridge.

Hristov, J., Toreti, A., Pérez Domínguez, I., Dentener, F., Fellmann, T., Elleby C., Ceglar, A., Fumagalli, D., Niemeyer, S., Cerrani, I., Panarello, L., Bratu, M., (2020). Analysis of climate change impacts on EU agriculture by 2050, EUR 30078 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-10617-3, doi:10.2760/121115, JRC119632

Huntington, T (2021). Aquatic Debris from European Aquaculture - Advice to the Aquaculture Advisory Council. Report produced by Poseidon Aquatic Resources Management Ltd for the AAC. 18 pp plus appendices.

Jones, A., H. Alleway, D. McAfee, P. Reis-Santos, S. Theuerkauf and R. Jones (2022). Climate-Friendly Seafood: The Potential for Emissions Reduction and Carbon Capture in Marine Aquaculture, *BioScience*, Volume 72, Issue 2, February 2022, Pages 123–143, https://doi.org/10.1093/biosci/biab126

Kim, B., R. Santo, A. Scatterday, J. Fry, C. Synk, S. Cebron, M. Mekonnen, A. Hoekstra, S. de Pee, M. Bloem, R.Neff & K.Nachman (2020). Country-specific dietary shifts to mitigate climate and water crises. *Global Environmental Change*, Vol. 62, https://doi.org/10.1016/j.gloenvcha.2019.05.010.

Kreiss C., E. Papathanasopoulou, K. Hamon, J. Pinnegar, S. Rybicki, G. Micallef, A. Tabeau, A. Cubillo & M. Peck (2020). Future socio-political scenarios for aquatic resources in Europe: an operationalized framework for aquaculture projections. *Frontiers in Marine Science*. 2020 Sep 29. DOI: https://doi.org/10.3389/fmars.2020.568159

MacLeod, M.J., M.R. Hasan, D. Robb & M. Mamun-Ur-Rashid (2020). Quantifying greenhouse gas emissions from global aquaculture. *Sci Rep* 10, 11679 (2020). https://doi.org/10.1038/s41598-020-68231-8

Moore, D. (2020). A biotechnological expansion of shellfish cultivation could permanently remove carbon dioxide from the atmosphere. *Mexican Journal of Biotechnology* 2020, 5(1):1-105. 1-10. 10.29267/mxjb.2020.5.1.1.

O'Neill, E., A. Morse & N. Rowan (2022). Effects of climate and environmental variance on the performance of a novel peatland-based integrated multi-trophic aquaculture (IMTA) system: Implications and opportunities for advancing research and disruptive innovation post COVID-19 era. *Science of The Total Environment*, Vol. 819, 2022, https://doi.org/10.1016/j.scitotenv.2022.153073

Payne, M., J. Pinnegar, M. Kudahl, G. Engelhard & M. Peck (2020). Ranking the vulnerabilities of fisheries and aquaculture species and sectors to climate change. CERES Deliverable 5.3. 70 pp. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cc9c4a7d&appId=PPGMS

Peck, M., I. Catalán, D. Damalas, M. Elliott, J. Ferreira, K. Hamon, P. Kamermans, S. Kay, C. Kreiß, J. Pinnegar, S. Sailley & N. Taylor (2020). Climate Change and European Fisheries and Aquaculture*: 'CERES' Project Synthesis Report*. Hamburg. DOI: 10.25592/uhhfdm.804.

Pham, T., R. Friðriksdóttir, C. Weber, J. Viðarsson, N. Papandroulakis, A. Baudron, P. Olsen, J. Hansen, U. Laksá, P. Fernandes, T. Bahri, S. Ragnarsson and M. Aschan (2021). Guidelines for co-creating climate adaptation plans for fisheries and aquaculture. *Climatic Change* 164, 62 (2021). https://doi.org/10.1007/s10584-021-03041-z

Rebl A, Verleih M, Korytář T, Kühn C, Wimmers K, Köllner B, Goldammer T (2012). Identification of differentially expressed protective genes in liver of two rainbow trout strains. *Vet Immunol Immunopathol.* 2012 Jan 15;145(1-2):305-15. doi: https://pubmed.ncbi.nlm.nih.gov/22196148/

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

Stavrakidis-Zachou, O., Papandroulakis, N., Sturm, A., Anastasiadis, P., Wätzold, F. and Lika, K. (2018). Towards a computer-based decision support system for aquaculture stakeholders in Greece in the context of climate change, *Int. J. Sustainable Agricultural Management and Informatics*, Vol. 4, Nos. 3/4, pp.219–234.

Stewart-Sinclair P., K. Last, B. Payne & T. Wilding (2020). A global assessment of the vulnerability of shellfish aquaculture to climate change and ocean acidification. *Ecol Evol*. 2020 Mar 12;10(7):3518-3534. doi: 10.1002/ece3.6149. PMID: 32274006; PMCID: PMC7141013.

Sundt, P., (2018). Sources of microplastics-pollution to the marine environment. https://vannforeningen.no/wp-content/uploads/2018/02/1.-Sundt.pdf

Sundt, P., P-E Schlze & F. Syversen (2014). Sources of microplastics-pollution to the marine environment. Presentation to the Norwegian Environment Agency (Miljødirektoratet). 108 pp.

Taylor, N., A. Kennerley & C. Kreiß (2019). Report on minimising economic losses, opportunities and challenges for aquaculture in Europe. Deliverable D4.2. Climate change and European aquatic RESources. 142 pp. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c7cfc5cc&appId=PPGMS

Winther, U., E. Hognes, S. Jafarzadeh and F. Ziegler (2020). Greenhouse gas emissions of Norwegian seafood products in 2017. Report published by SINTEF for the *Norwegian Seafood Research Fund* (FHF) in June 2020. 114 pp. https://www.sintef.no/contentassets/25338e561f1a4270a59ce25bcbc926a2/report-carbon-footprint-norwegian-seafood-products-2017_final_040620.pdf/

Yumashev, D., C. Hope, K. Schaefer, K. Riemann-Campe, F. Iglesias-Suarez, E. Jafarov, E. Burke, P. Young, Y. Elshorbany and G. Whiteman (2019). Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements. *Nat Commun* 10, 1900 (2019). https://doi.org/10.1038/s41467-019-09863-x

Appendix B: Supporting materials

Figure 2: EU agricultural outputs (2018 – 2020)

Output components (real prices)	2018	2019	2020 (e)	
	Million EUR		Million EUR	% of total
Cereals	**41 243**	**42 191**	**40 782**	**21.0%**
Wheat and spelt	19 394	20 041	18 962	9.7%
Rye and meslin	823	998	1 127	0.6%
Barley	7 544	7 786	7 411	3.8%
Oats and summer cereal mixtures	1 228	1 250	1 443	0.7%
Grain maize	9 985	9 621	9 467	4.9%
Rice	654	706	689	0.4%
Other cereals	1 616	1 788	1 683	0.9%
Industrial crops	**17 940**	**16 580**	**16 555**	**8.5%**
Oil seeds and oleaginous fruits	9 356	8 514	9 016	4.6%
Protein crops	1 101	1 113	1 093	0.6%
Raw tobacco	528	524	496	0.3%
Sugar beet	2 660	2 619	1 718	0.9%
Other industrial crops	4 296	3 810	4 232	2.2%
Forage plants	**20 459**	**22 173**	**21 963**	**11.3%**
Vegetables and horticultural products	**49 318**	**51 996**	**51 645**	**26.5%**
Potatoes	**10 958**	**12 834**	**10 811**	**5.6%**
Fruits	**27 929**	**25 433**	**27 351**	**14.1%**
Wine	**25 278**	**20 671**	**19 985**	**10.3%**
Olive oil	**4 523**	**5 143**	**3 465**	**1.8%**
Other crop products	**2 082**	**2 126**	**1 972**	**1.0%**
Crop output	**199 731**	**199 148**	**194 529**	**57.9%**
Animals	**83 639**	**86 470**	**83 374**	**59.0%**
Cattle	26 782	25 548	24 482	17.3%
Pigs	32 014	36 231	35 205	24.9%
Equines	1 013	962	864	0.6%
Sheep and goats	3 545	3 472	3 505	2.5%
Poultry	18 145	18 091	17 275	12.2%
Other animals	2 141	2 166	2 042	1.4%
Animal products	**60 204**	**59 047**	**57 998**	**41.0%**
Milk	48 806	48 609	47 728	33.8%
Eggs	8 769	8 197	8 083	5.7%
Other animal products	2 629	2 242	2 187	1.5%
Animal output	**143 843**	**145 517**	**141 372**	**42.1%**
Agricultural goods output	**343 574**	**344 665**	**335 901**	**100.0%**

Source: https://agriculture.ec.europa.eu/document/download/6aa74b11-9ea9-454d-80df-53e0c9cfe3f8_en?filename=agri-statistical-factsheet-eu_en.pdf

Figure 3: Climate change impacts in Europe

Arctic region
- Temperature rise much larger than global average
- Decrease in Arctic sea ice coverage
- Decrease in Greenland ice sheet
- Decrease in permafrost areas
- Increasing risk of biodiversity loss
- Some new opportunities for the exploitation of natural resources and for sea transportation
- Risks to the livelihoods of indigenous peoples

Atlantic region
- Increase in heavy precipitation events
- Increase in river flow
- Increasing risk of river and coastal flooding
- Increasing damage risk from winter storms
- Decrease in energy demand for heating
- Increase in multiple climatic hazards

Mountain regions
- Temperature rise larger than European average
- Decrease in glacier extent and volume
- Upward shift of plant and animal species
- High risk of species extinctions
- Increasing risk of forest pests
- Increasing risk from rock falls and landslides
- Changes in hydropower potential
- Decrease in ski tourism

Coastal zones and regional seas
- Sea level rise
- Increase in sea surface temperatures
- Increase in ocean acidity
- Northward migration of marine species
- Risks and some opportunities for fisheries
- Changes in phytoplankton communities
- Increasing number of marine dead zones
- Increasing risk of water-borne diseases

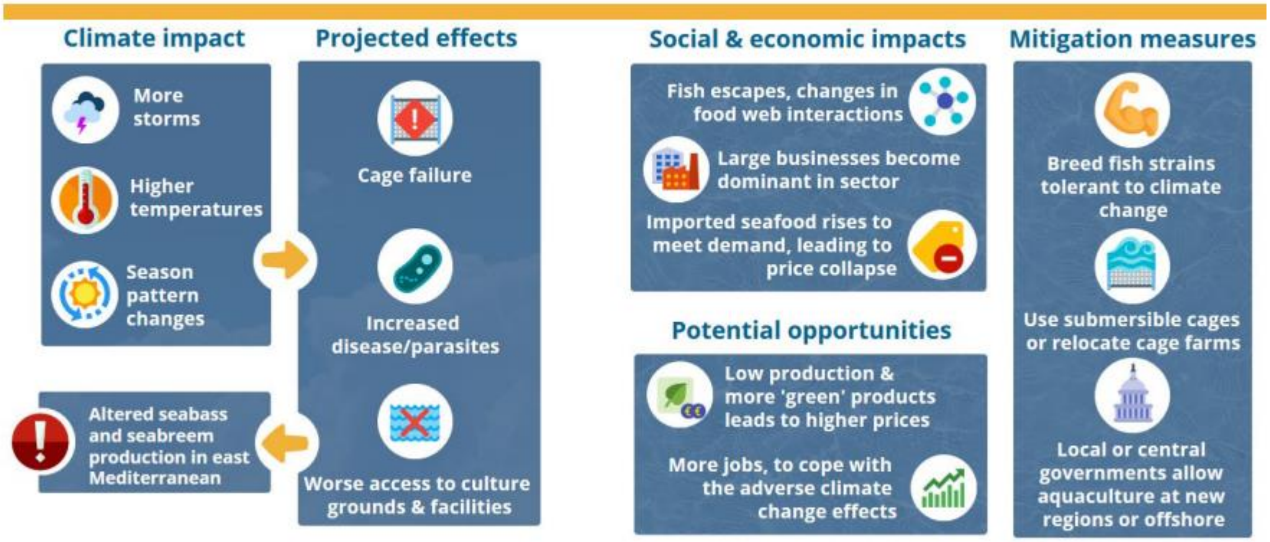
Boreal region
- Increase in heavy precipitation events
- Decrease in snow, lake and river ice cover
- Increase in precipitation and river flows
- Increasing potential for forest growth and increasing risk of forest pests
- Increasing damage risk from winter storms
- Increase in crop yields
- Decrease in energy demand for heating
- Increase in hydropower potential
- Increase in summer tourism

Continental region
- Increase in heat extremes
- Decrease in summer precipitation
- Increasing risk of river floods
- Increasing risk of forest fires
- Decrease in economic value of forests
- Increase in energy demand for cooling

Mediterranean region
- Large increase in heat extremes
- Decrease in precipitation and river flow
- Increasing risk of droughts
- Increasing risk of biodiversity loss
- Increasing risk of forest fires
- Increased competition between different water users
- Increasing water demand for agriculture
- Decrease in crop yields
- Increasing risks for livestock production
- Increase in mortality from heat waves
- Expansion of habitats for southern disease vectors
- Decreasing potential for energy production
- Increase in energy demand for cooling
- Decrease in summer tourism and potential increase in other seasons
- Increase in multiple climatic hazards
- Most economic sectors negatively affected
- High vulnerability to spillover effects of climate change from outside Europe

Source: https://www.europarl.europa.eu/news/en/headlines/priorities/climate-change/20180703STO07123/climate-change-in-europe-facts-and-figures

Figure 4: Bottom-up climate change mitigation measures (sea bass & sea bream in the eastern Mediterranean



Source: CERES

Figure 5: The various metrics used at either the species (fish and shellfish) or national level (22 countries) to rank the vulnerability of the European aquaculture sector

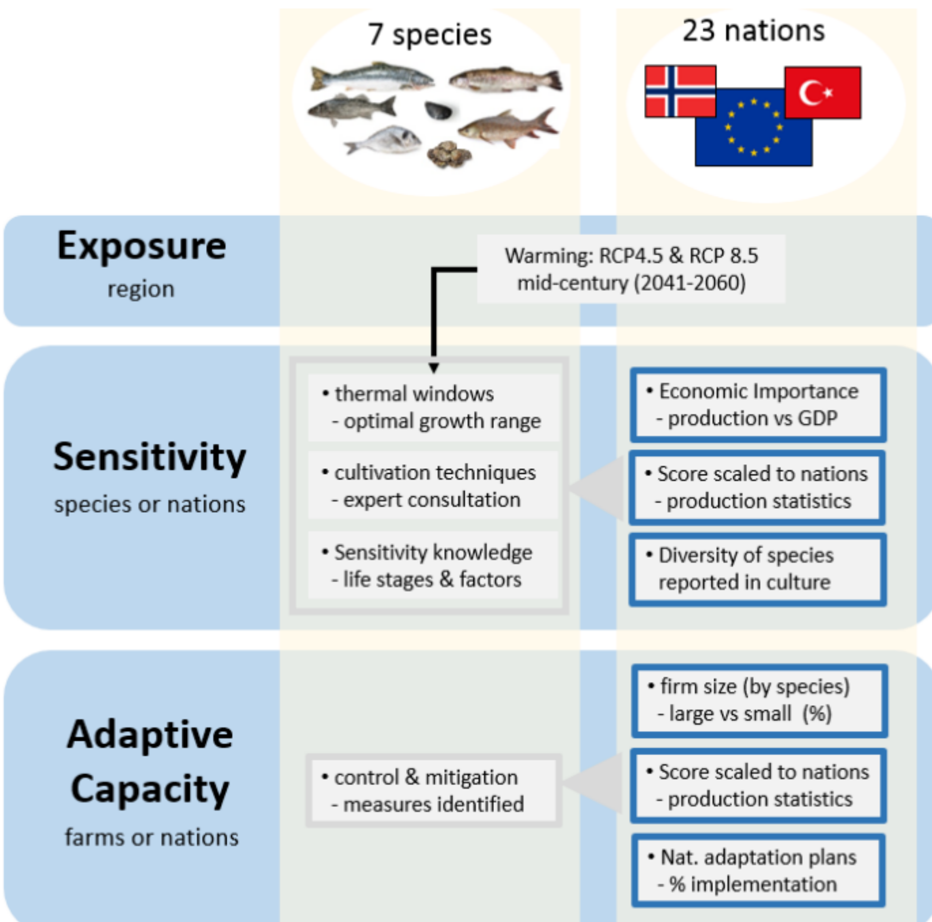
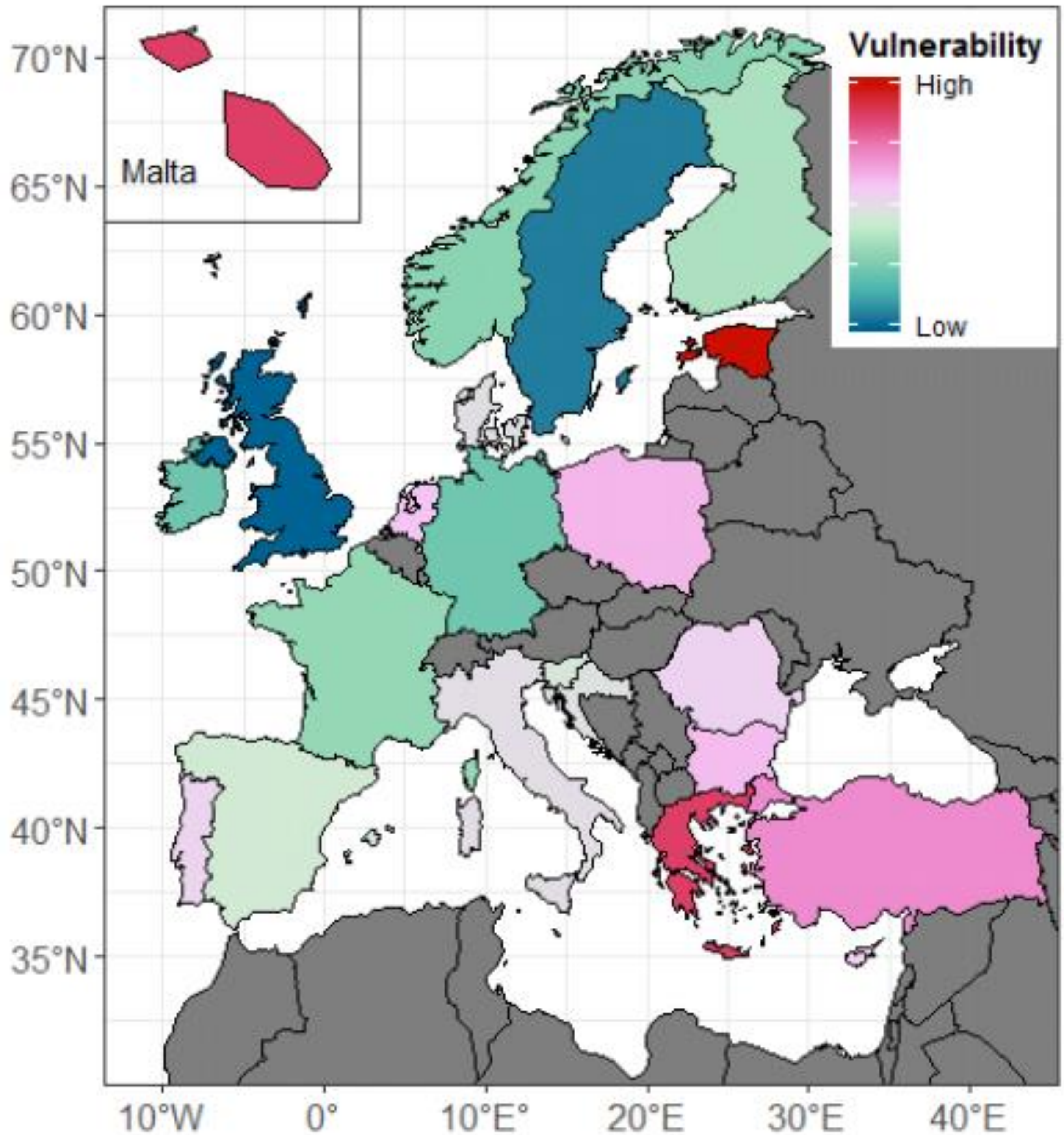


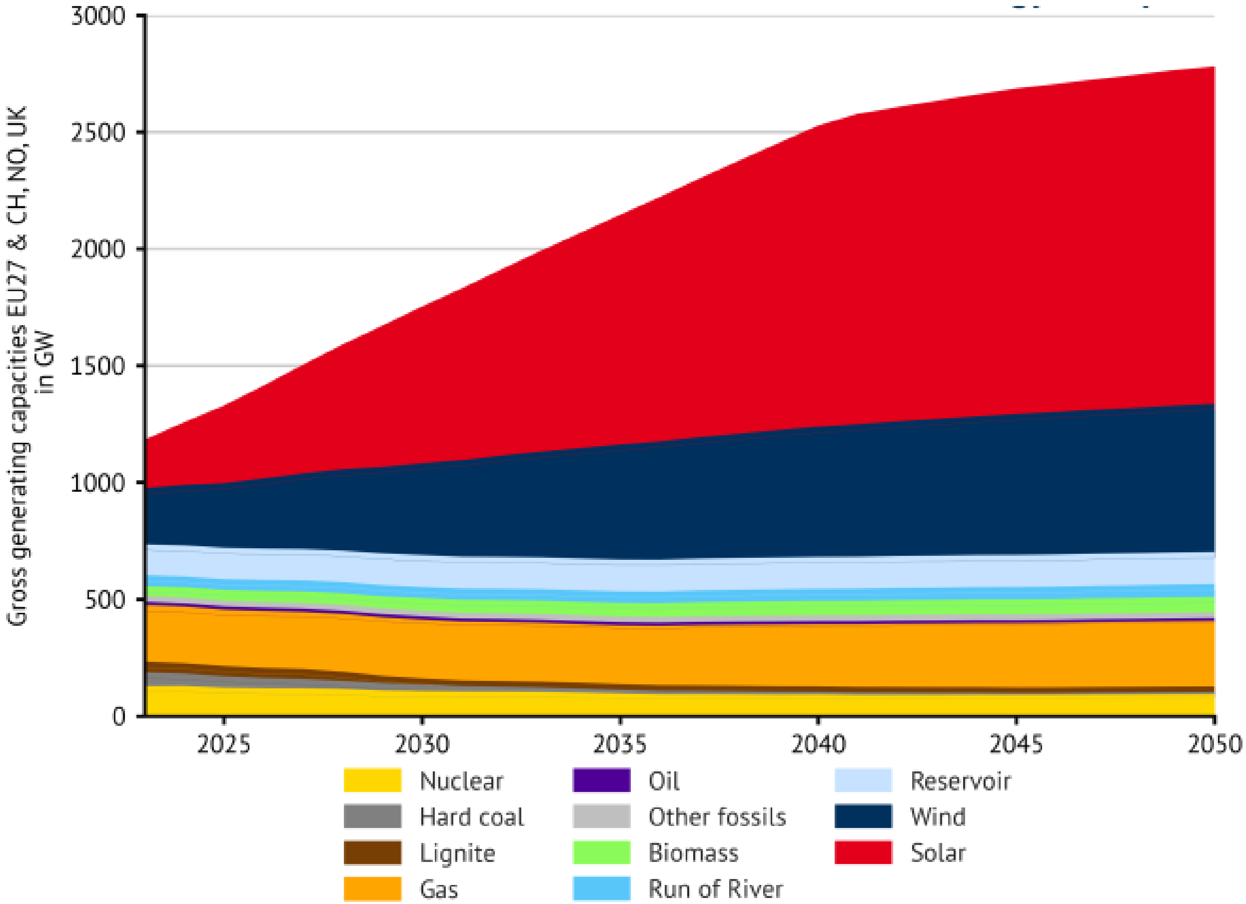
Figure 6: National-level scores for vulnerability of aquaculture to climate change

On a relative scale from low to high, based on the species grown and various metrics of *Exposure*, *Sensitivity* and *Adaptive Capacity* (see **Section 3.1** for more details).



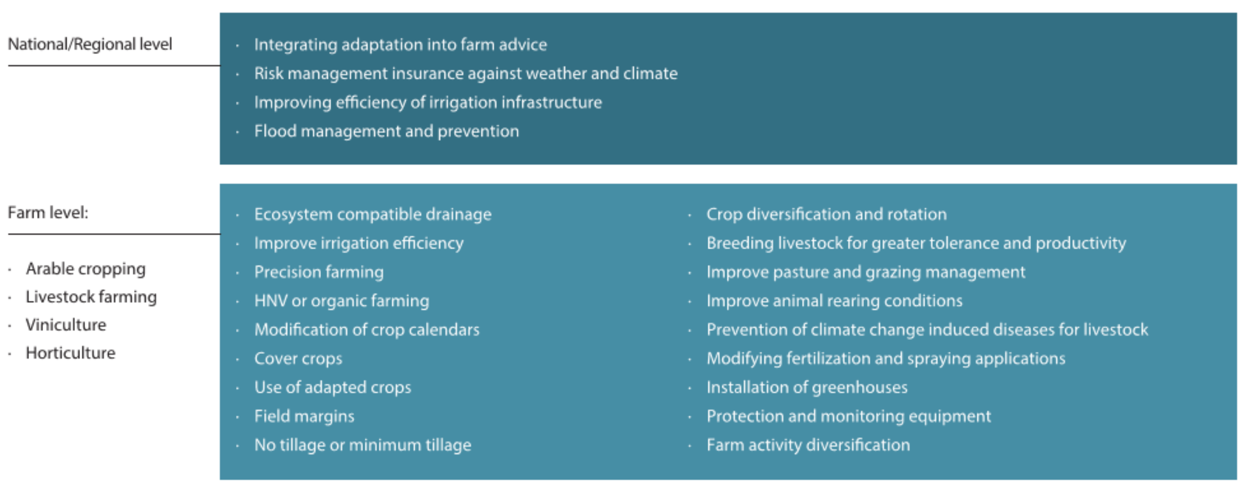
Source: Payne *et al*, 2020

Figure 7: Installed generation capacities in EU-27 (plus NO, CH and UK) by energy source



Source: Energy Brainpool (2021). Derived from: EU Reference Scenario (EC, 2016) 7 entso-e (2021)

Figure 8: Selection of adaptation measures at national, regional and farm levels in European agriculture



Source: EEA, 2020

Notes

Poseidon Aquatic Resource Management Europe Limited

Ground Floor, 71 Lower Baggot Street, Dublin D02 P593, Ireland

Telephone: +44 1590 610168
tim@consult-poseidon.com
http://www.consult-poseidon.com