Spotlighting Adaptation Solutions to Enhance the Resilience of Mediterranean Aquaculture to Climate Change

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DISCLAIMER

Data Classification Approach for the AquaMedCC Report "Spotlighting Adaptation Solutions to Enhance the Resilience of Mediterranean Aquaculture to Climate Change".

Readers should note a methodological distinction in how aquaculture production environments are classified in this handbook compared to the FAO databases. This report categorizes water types strictly based on the FAO's salinity definitions, where brackish water is defined as having a salinity between 0.5‰ and 20‰. Because many of Egypt's coastal and delta ponds fall into this salinity range, this handbook categorizes Egypt's massive Nile tilapia and mullet production as brackish, making brackish water the dominant aquaculture system in our baseline analysis (~54% of regional production). Conversely, datasets such as the FAO's The State of Mediterranean and Black Sea Fisheries 2025 aggregate this specific Egyptian production under freshwater (likely based on the biological profile of the species or national reporting standards). The physical realities on the ground remain the same. According to the FAO 2025 report, regional production is 58% freshwater, 36% marine, and 6% brackish. For the vulnerability assessment, cross-cutting discussions and evaluations in this handbook, the baseline numbers noted in the AquaMedCC tables have been used.

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I. Introduction

Plan Bleu is one of the six Regional Activity Centres of the United Nations Environment Programme's Mediterranean Action Plan (UNEP/MAP). These six regional centers are delegated by the twenty-two Contracting Parties to the Barcelona Convention and are responsible for the implementation of the Convention's seven Protocols. Within this framework, Plan Bleu serves as an observatory of sustainable development in the Mediterranean region. Its mission is to provide thematic, systemic, and strategic foresight analyses that aim to inform stakeholders and decision-makers on major environmental risks and levers for sustainable development. A key task is, for instance, the revision and drafting of the Mediterranean Strategy for Sustainable Development (MSSD), which provides a strategic policy framework for securing a sustainable future for the Mediterranean region in line with the Sustainable Development Goals (SDGs).

Aquaculture development is recognized as a major component of the Blue Economy strategy for the Mediterranean basin and by Plan Bleu. In fact, in 2020-2021, Plan Bleu brought together a group of experts (around 80 scientific, institutional, and private-sector players) specialized in Mediterranean aquaculture. Through various technical meetings including two webinars organized in collaboration with the Food and Agriculture Organization (FAO) and the General Fisheries Commission for the Mediterranean (GFCM), this working group discussed current issues relating to this growing sector of activity in the Mediterranean. Following these meetings, nine major areas of action and thematic priorities for governance dialogue were identified and highlighted in a roadmap, declinable at regional level. The Mediterranean basin is particularly vulnerable to climate change (CC), with impacts such as the frequency of extreme weather events expected to be amplified in this region. Therefore, in 2023, Plan Bleu has launched the Mediterranean Aquaculture and Climate Change project (MedAquaCC) with two senior experts specialized in sustainable aquaculture. Within this project, a semi-quantitative questionnaire was disseminated to 80 stakeholders, and an exhaustive desk literature review was conducted by two external consultants, resulting in a rich scoping study. The gained insights need to be made applicable for aquaculture farmers to support and empower them during climate adaptation processes. Thus, the scoping study was reorganized and merged with additional desk research and the semi-quantitative questionnaire by the Plan Bleu to create an informative handbook for Mediterranean aquaculture farmers.

This handbook integrates into Plan Bleu's existing efforts by highlighting climate adaptation and mitigation options for Mediterranean aquaculture farmers. It aims to provide a solid and useful baseline for adaptation and mitigation actions while strengthening the resilience of the Mediterranean aquaculture sector to CC. The handbook offers a summary of the state of Mediterranean aquaculture, a vulnerability assessment, the identification of problems faced by aquaculture farmers coupled with solutions for CC adaptation and mitigation, and a compilation of best practices in aquaculture to foster resilience and sustainability.

II. Methodology

The study was based on extensive desk research conducted by two external consultants, complemented and reorganized by the Plan Bleu. A questionnaire with 25 questions was developed and disseminated among professionals working in the aquacultural sector, resulting in 80 persons participating. A multi-criteria analysis of this questionnaire was performed. Cross-references in the text to the questionnaire are marked with Question (Q) and the question's number respectively.[1]

In Chapter 4 III, a vulnerability assessment was performed based on an existing study by Handisyde *et al.* (2017). The researcher investigated the vulnerability of aquaculture-related livelihoods to climate change at a global scale (1), which was also used by the FAO in their Annual Report on the state of fisheries in 2018 (2). In the present report, the assessment was applied to the Mediterranean context. In this way, Mediterranean countries are set in relation to each other and a vulnerability classification, ranging from relatively low to high vulnerability is provided. The vulnerability was calculated based on a function of exposure to climate change, sensitivity to climate change, and adaptive capacity, which is a common method for vulnerability assessments also used by the IPCC in their third assessment report (3).[2]

Regional normalization was performed by excluding all vulnerability values for countries outside the Mediterranean region. This results in a map of differentiated vulnerability value for the Mediterranean countries per production type that can be compared and put into relation within the region and production type. Marine aquaculture was excluded from this analysis due to data deficiency. The color classes indicate vulnerability relative to other countries within the same type of aquaculture and the Mediterranean region and is not intended to be a means of comparing vulnerability between different aquaculture types or other areas outside the Mediterranean basin.

Table 2 in Chapter III B represents one of the core elements of this report. Unlike other existing approaches, a problem-solution perspective is adopted. This means that farmers should be able to find one of the self-identified problems or direct impacts in Table 2, find out more about the potential CC cause, and receive more information on how he or she could adapt the farm and/or mitigate the cause of the problem. The table presents a non-exhaustive list of possible problems in aquaculture due to CC is ranked from A1 to E1, according to their severity and urgency to act. This compilation aims to assist aquaculture farmers with actionable knowledge. Thereby their expertise in identifying operational problems should be recognized and integrated to specifically address these problems and mitigate their CC-related causes. To assure the quality of this report, proofreading was performed with two internal and one external expert, specialized in climate adaptation and sustainable aquaculture.

A. Characteristics and common practices of Mediterranean aquaculture

Before diving into the vulnerability assessment and climate change impacts and adaptation possibilities it is essential to have a clear vision on the state of aquaculture in the Mediterranean basin. Therefore, the spatial distribution with the key producing countries and main farmed species is assessed in the following according to the three major system types found in the Mediterranean: freshwater, brackish water, and marine water. This allows to structure and narrow down the scope of this work, facilitating a wide-spread applicability in the Mediterranean basin. Nevertheless, it is essential to find adaptation solutions that are tailored to local contexts and to also develop and adapt aquaculture productions that currently still play a secondary role in the Mediterranean to allow a diversification of the sector. This would exceed the objective of this study and could be done in a further step by local or regional actors, following a similar methodology.

1. Spatial distribution of Mediterranean aquaculture

The total aquaculture production in countries bordering the Mediterranean and the Black Sea was around 3 299 000 tonnes in 2021 (5). Egypt, Turkey, Greece, and Italy hold more than 80% of the total production weight of the Mediterranean aquaculture (7). Particularly, Egyptian aquaculture plays a pivotal role, as it is the largest aquaculture industry in Africa, currently considered the main source of fish supply accounting for almost 79% of the total fish

[1] More information on the questionnaire can be provided by the authors on request.
[2] More information about the methodology of the vulnerability assessment can be found in (1) and in the Appendix 9.1.

production of the country (1.59 million tonnes/year) (8). Therefore, a focus will be placed on these countries in the recommendations section (cf. 5). However, several countries are in an early developing stage of the aquaculture sector, and they already have ambitious aquaculture expansion plans and strategies for the following years, as this can be seen in Morocco and could also benefit from this work.

2. Key Species in Mediterranean Aquaculture

Gilthead seabream, European seabass, Flathead grey mullet, and Mediterranean mussel account for nearly 90% of the marine aquacultural production weight in the Mediterranean basin (7). Considering freshwater and brackish water aquaculture, Nile tilapia, and Rainbow trout are major species to consider (9). Therefore, it is essential to find adaptation strategies for these species, while at the same time diversifying the Mediterranean aquacultural landscape. Diversified aquaculture is expected to be less vulnerable than monocultures, to rapid disease outbreaks, and other related CC-indulged stressors (10)(11).

In general, a trend to more finfish (83%) instead of mollusks (16%) for marine aquaculture could be observed in the last years (7). Why this could be problematic will be discussed in chapter III.

3. System types of Mediterranean aquaculture

The Mediterranean aquacultural system could be divided according to the water type used: marine, brackish, and freshwater aquaculture. Here are the respective definitions used in this report:

- Marine aquaculture is defined as the cultivation of the end product taking place in seawater. This is often done in inshore and open waters, or inland seas in which the salinity generally exceeds 20‰ (12)[3].
- Brackish aquaculture describes the cultivation of aquatic organisms where the product is raised in brackish water, such as in estuaries, coves, bays, and lagoons, with a salinity between 0.5‰ and 20‰ (12).
- In freshwater aquaculture, the end product of the aquatic organisms is raised in freshwater, such as reservoirs, rivers, lakes, and canals, in which the salinity stays below 0.5‰ (12).

Marine (25%) and freshwater (21%) account together for around half of the Mediterranean aquacultural production in 2019. The main production takes place in brackish waters with around 54**%**. The key species and major producing countries for each water type are listed in Table 1. A key player in the Mediterranean is Egypt, accounting for more than 80% of brackish aquaculture (9).

Table 1. Characterization of Marine, Brackish and Freshwater Aquaculture in the Mediterranean

	Marine	**Brackish**	**Freshwater**
Total production MED and black sea 2021 (in %) Total: 3 299 000t(5)	~ 25% in 2016 (13)	~ 54 % in 2016 (13)	~ 21 % in 2016 (13)
Main species (9)	**Gilthead seabream** *Sparus aurata* **European seabass** *Dicentrarchus labrax* **Mediterranean Mussel** *Mytilus galloprovincialis*	**Nile tilapia** *Oreochromis niloticus* > 50% **Flathead grey mullet** *Mugil cephalus*	**Rainbow trout** *Oncorhynchus mykiss* > 50% **Flathead grey mullet** *Mugil cephalus*
Countries (9)	Greece, Italy, Turkey	Egypt >80%	Egypt, Turkey, France, Italy

In general, marine finfish can be produced on land, inshore, in ponds, sea net pens, and tanks (including Recirculating Aquaculture Systems (RAS) and flow through open systems), while shellfish production systems are divided into:

[3] Please refer to the 'Methodological Disclaimer' on page 2 regarding the data classification approach used for these baseline figures and a comparison with the updated FAO 2025 data.

shellfish rafts and longlines, bottom, and intertidal shellfish culture (14). Other branches like the macroalgal and microalgal productions are in their infancy, with very few operating farms (e.g., Greensea in France (15)), and a growing interest in Morocco, Algeria, and Tunisia.

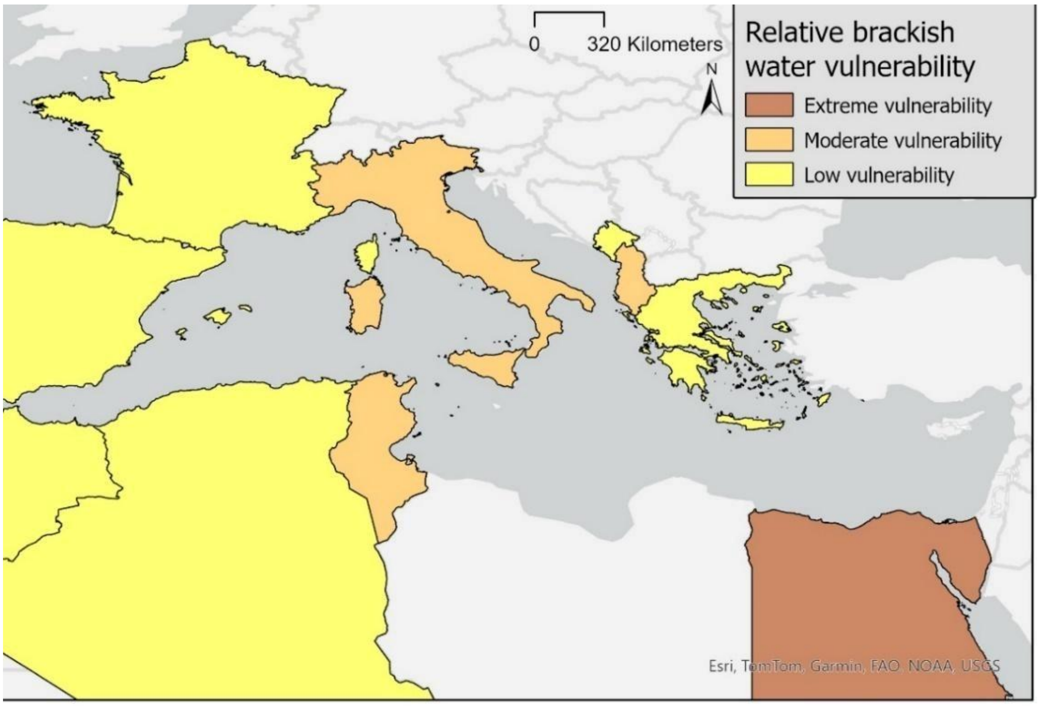
- **Major producing countries: Egypt, Turkey, Greece, and Italy.**
- **The main species used in Mediterranean aquaculture: Gilthead seabream, European seabass, Mediterranean mussel, Nile tilapia, Rainbow trout, and Flathead grey mullet.**
- **Egypt is the major producing country for the Mediterranean basin and makes brackish aquaculture the most dominant aquacultural type.**

III. Vulnerability of Mediterranean aquaculture due to CC

Vulnerability assessment of aquaculture in the Mediterranean basin was identified as a major requirement for Research and Development in the questionnaire (Q15). As climate change impacts differ between different regions, it is essential to identify various vulnerability levels of Mediterranean aquaculture to provide solutions and design effective recommendations that address the most pressing needs in a region. Therefore, a first rough vulnerability assessment is provided and synthesized in a map in this chapter.

Figure 1and Figure 2 illustrate the normalized relative aquaculture vulnerability for brackish and freshwater Mediterranean aquaculture. The color gradient indicates vulnerability relative to other countries within the same type of aquaculture and the Mediterranean region and is not intended as a means to compare vulnerability between different aquaculture types or other areas outside the Mediterranean basin.[4]

Figure 1. Normalized relative brackish water aquaculture vulnerability in the Mediterranean



Source: Handisyde et al. (2017). Conception: map realized on ArcGIS software, Plan Bleu (2024)

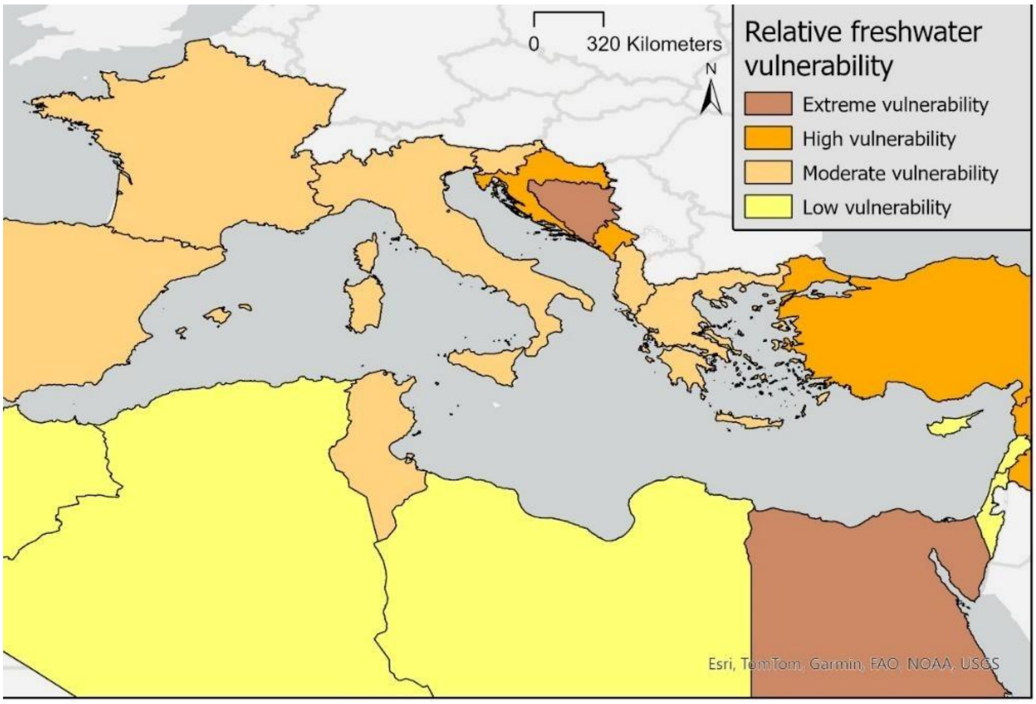
The vulnerability assessment of brackish aquaculture showed that Egyptian aquaculture-related livelihoods are by far the most vulnerable. As sensitivity was measured in kg per capita and contribution of aquaculture production to the national GDP as part of the vulnerability calculation, Egyptian aquaculture-related livelihoods are classified much morevulnerable compared to other Mediterranean countries. It accounts for over 80% of Mediterranean brackish aquaculture and is therefore of particular importance for the development of the national economy.

Furthermore, it has been observed in many regions (on both rims) that ground salinization may induce activity sector reconversions. For example, coastal rice fields have been transformed into brackish-water aquaculture farms. This trend already affects and should be increasingly pronounced in Italy (the valli of the Po plain), France (the Camargue,

[4] More information about the methodology of the vulnerability assessment can be found in (1) and in the Appendix 9.1.

certain Occitan lagoons), Spain (the Ebro delta), Morocco (the Nador lagoon), Tunisia (the lagoons of the Gulf of Gabès), Turkey (the Gulf of Antalya and the Iskenderun lagoons), Greece (the Thessaloniki plain), etc. In fact, Egyptian aquaculture recorded an increase of +1.5 million tonnes by applying this sectoral conversion over the period 1990-2020. On a MENA scale, this increase can be translated into a significant change in per capita consumption, which rises from 9 kg/capita/year to 20 kg/capita/year (equivalent world average) for the 105 million Egyptians.

Figure 2. Normalized relative freshwater aquaculture vulnerability in the Mediterranean



Source: Handisyde et al. (2017). Conception: map realized on ArcGIS software, Plan Bleu (2024).

Similarly, Egypt also received high vulnerability scores for freshwater aquaculture, as its leading position in this sector is associated with a dependence of livelihoods, and thus vulnerability to climate impacts. Egypt is followed by Bosnia and Herzegovina, Turkey, Croatia, and Montenegro.

This analysis provides an overall impression of the vulnerability of aquaculture-related livelihoods to climate change in the Mediterranean. However, different farm sites and regions are exposed to varying local climate impacts, which can be more intense than the national reference depicted here. Therefore, **local vulnerability assessments** are crucial to provide more accurate information on local CC impacts and more precise adaptation measures accordingly. In addition, adaptive capacity should be complemented in future studies by indicators other than the Human Development Index (HDI). This could include, for instance, technical know-how or already initiated climate adaptation measures or developed strategies.

After classifying the Mediterranean countries by their aquaculture's vulnerability degree, this section gives reasons, why these differences exist. On the one hand, Northern Mediterranean Countries (NMCs) focus their aquacultural production on **high-value products for tourism and export markets** (16). This puts them in a position of being dependent on market fluctuations and geopolitical situations, which has been demonstrated during the Covid pandemic (17). As pandemics are expected to happen more often due to CC and biodiversity crises, this could massively increase the aquaculture vulnerability of NMCs. However, the proportional contribution of aquaculture to the national GDP is relatively low, which decreases the vulnerability of livelihoods on a national level. The individual farmers or regions would still be impacted, which underlines again the need for local vulnerability assessments. Contrary, South Eastern Mediterranean Countries (SEMCs) focus on food security and local communities, which potentially could be a more promising approach to accelerate the sustainable development of Mediterranean aquaculture. Other factors that could cause regional vulnerability differences are environmental factors such as temperature differences, varying amounts of freshwater imports or influences from surrounding water systems and infrastructures like dams. These factors have to be taken into consideration for future, more detailed vulnerability assessments.

Next to the spatial differentiation of the vulnerability risks in the sector, the different parts of the value chain should be emphasized and classified. According to the questionnaire, the **producers** are the most vulnerable part of the value chain (Q19). 38 out of 41 participants said that there is a risk that they have to quit their activity in the future (Q23). Nearly all of the aquaculture producers said that they may have to quit their activities due to CC, especially if nothing is done in the future. The only farmer who said "No, there is no risk" has a RAS production in Portugal, where he or she did not observe any differences in production due to CC (participant number 70). RAS as a potential CC adaptation solution is described in more detail in Chapter III.C.

Within the producers, there are again different levels of vulnerability, dependent on their adaptive capacities to CC, which are, for instance, largely dependent on their size. Small and Medium Enterprises (**SMEs**) are expected to be most vulnerable (18).

Figure 3 Production as the most vulnerable part of the aquacultural value chain (Q19)

To conclude, this chapter only gives an idea about a general vulnerability risk. However, farm-specific and regional vulnerability assessments are key to being able to adapt to the diverse local contexts and CC impacts, species needs, and differing production systems.

A great Marine Spatial Planning (MSP) tool developed by Palauan authorities, The Nature Conservancy and NASA, assesses the site suitability for aquaculture in Palau. It takes into account multiple factors like CC impacts, protected habitats or areas highly used for other sectors like tourism or maritime traffic (19) (20) (21). This approach facilitates the user experience with interactive cartographic representations and is very precise and useful for aquaculture site recommendations. If adapted to the Mediterranean context, this would be an immensely helpful resource for aquaculture farmers and spatial planners. This tool can further be explored here: https://www.maps.tnc.org/palau-aquaculture/#/

A. CC VULNERABILITY OF MAJOR COMMERCIAL MEDITERRANEAN SPECIES

The two main species for marine aquaculture in the Mediterranean are Gilthead seabream and European seabass. The time-to-market size of **Gilthead seabream** (*Sparus aurata*) is likely to decrease with temperature increase due to climate change, from currently 450 days to a potential reduction of 36% (22). While this symbolizes a positive impact in the mid-term, these impacts translate into negative ones in the long term. At some point, higher summer surface temperatures will exceed the benefit of warmer winter temperatures and become problematic for seabream and seabass production. Especially thermal stress will result in lower growth and higher disease susceptibility. Novel bacterial pathogens like *Edwardsiella anguillarum* were identified in Greece to already cause problems in reared sharp snout seabream (10) These impacts are likely to be the most extreme in the most productive areas of the Levantine, Aegean, and Adriatic seas, and coastal waters of Tunisia (22).

Whether Gilthead seabream or European seabass is better adapted to increasing temperatures remains controversial, as some studies would recommend Gilthead seabream (22) and other European seabass (10) However, meagre appears to be the most resilient to warming conditions compared to the other two species (10)

A study in Greece on **European seabass** (*Dicentrarchus labrax*) and Meagre showed a general short-term increase in time-to-market size until 2030 and a decrease in time-to-market size up to 2050 (6). Moreover, some farmers shifted from seabass to meagre, as through their fast growth and shorter time-to-market, the meagre holds a lower risk of being exposed to extreme weather events (6, 23). In addition, meagre was often mentioned as a species with a higher CC tolerance, compared to seabream and seabass (6). Therefore, Meagre could be seen as a potential future alternative as it has a higher optimal temperature range (14-26°C for adults, 26-30°C for rearing juveniles) compared to seabream and seabass (10). While increased growth rate could be a positive CC impact this often comes with thermal stress and security to diseases. Bacterial diseases like *Aeromonas veronii* already pose a significant threat to the European seabass industry in Greece and Turkey, which is expected to increase with rising temperatures in the next years (10).

For the **Mediterranean mussel** (*Mytilus galloprovincialis*)**,** it can be stated that in general the mussel production especially in Italy, Greece, France, and Spain will be heavily impacted by ocean acidification. This hinders the construction of calcareous skeletons and shells that depend on the use of carbonates (11).

Nile tilapia (*Oreochromis niloticus*) has an ideal temperature range for best growth between 26 and 30 °C and its thermal tolerance ranges from 14-32°C (24). This species could be more vulnerable to extreme changes in seawater intrusion (24). Research projects are currently in place elaborating on the molecular and genetic basis of hypoxia tolerance for Nile Tilapia and Rainbow trout (25).

Rainbow trout (*Oncorhynchus mykiss*) is one of the major freshwater species in the Mediterranean. It requires a high level of oxygen and relatively high-quality water and is thus highly impacted by environmental changes due to CC. Its preferred temperature ranges from 7-18°C, with an optimum around 13-15°C. At 21°C inflammation and liver tissue changes have been observed, with temperatures above 24°C leading to serious tissue injuries and a significant decrease in immune function.

Flathead grey mullet (*Mugil cephalus*) has a temperature tolerance range between 13-33°C with an optimum around 20-26°C (26). *M cephalus* depends mainly on wild fry, which limits expansion opportunities (7). Other CC impacts like a relatively high risk of salt intrusion could significantly increase the vulnerability of Flathead grey mullet (27).

Conclusion on the vulnerability of Mediterranean aquaculture:

- **Production is the most vulnerable part of aquaculture value chains.**
- **Aquaculture-related livelihood vulnerability assessment on a national level helps to get a first impression. However, there remains a huge need for local vulnerability assessments for farm-level adaptation activities.**
- **Meagre seems to be more temperature tolerant than Gilthead seabream and European seabass.**

B. PROBLEMS AND SOLUTIONS FOR CC IMPACTS ON MEDITERRANEAN AQUACULTURE

In the questionnaire, aquacultural sector professionals were asked to rate several direct CC impacts regarding their concern for impacting aquaculture (Q7). The following impacts were classified on average as concerning or highly concerning by the participants: (7a) water quality deterioration, (7b) increased disease frequency and/or severity, (7c) emergence of new pathogens, and (7j) sudden heavy losses due to environmental factors (e.g. anoxia, HAB, storms). Direct impacts give a hint on the farmer’s CC impacts awareness and are often similar to the problems farmers already face. Thus, a particular focus should be placed on these mentioned direct impacts, when formulating adaptation solutions.

Table *2* provides a non-exhaustive list of CC-related problems, causes, and solutions for aquaculture farmers. At the same time, this table presents a non-exhaustive list of problems, causes, and solutions. Having for instance “reduced fish appetite” as a potential problem observed by the farmer, does not mean that fish appetite will obligatorily reduce with enforced climate change, as it contrary could increase with higher temperature (28). The problems are ranked (A1-E1) by severity and urgency. The purpose of the table is to equip farmers with actionable knowledge to address their problems, by adapting to and/or mitigate the CC-related cause.

Table 2. Problems in the aquacultural sector due to CC and respective adaptation solutions

Problems on Farm-level	CC impact	Solutions	Additional Benefits & Opportunities	Best Practice Examples & Pilot Studies
A1: Reduced fish appetite	Hypoxia: Lower dissolved oxygen (DO) solubility at higher temperatures (18)	EWS (Argo floats, shipboard sensors) (25)		China: monitoring of temperature and DO in abalone cages (25)
		Improve circulation/aeration systems		Indonesia (29): paddle wheel aerator, (brackish (30)
		Shift to more tolerant species or strains (25)		Current research projects on molecular & genetic basis for hypoxia tolerance: Nile Tilapia, Rainbow trout (25)
A2: Reduced product quality / off-flavour product (2)	HAB	- EWS (2) - Depuration facilities & controlled environments production systems (RAS, ponds) - semi-recirculating systems in land-based aquaculture facilities during HAB or heatwave episodes(18)	Improved food security (31)	- Hazard Analysis and Critical Control Points (HACCP) (32) - South Africa, Abagold Limited(31) - Australia: for oyster farmers
B1: Reduced growth, metabolic rate	Temperature rise: - primary production changes due to changed water currents (33)	- adaptation of nutritional requirements and feeding strategies	Positive health effects (disease susceptibility) (31)	Feeds for main aquaculture-fed species for life stages and year periods by Le Gouvello and Simard (2017) (34)
	Hypoxia(2)	see A1		
	Salinity change	see E1		
embryo/larval (2)	Acidification	see E1		
B2: Destruction of facilities	Extreme weather events (sea level rise or storm surge damage)	Investments in protection infrastructure (dams, dikes) (2)	Lower risk of fish escape	
C1: Weakened immune system, reduced resilience	- Temperature rise - Sealevel rise higher salinity(2)	Genetic selection for climate-resilient strains		- Vietnam: salinity-resistant catfish (23) - temperature-tolerant salmon (23) - pH resistant mollusk larvae (23)
		Introduction of new species (better adapted to socio-environmental conditions)		- North America: Oyster (*Crassotrea virginica*) outperformed the blue mussel (*Mytilus edulis*)(35) - meager could be more CC tolerant than seabass(6)
		Introduction of non-native species		- France: switch to shrimp (36), production of tropical species (*Penaeus japonicus*) (37)
		Shift to lower trophic aquaculture (Micro- and macroalgae)	Positive impact on the environment, CC mitigation(38)	- Macroalgae (new species)(39), (offshore)(40) - Sea urchins: Spain(41) - Oyster(42) - Blue mussels (offshore) (43)
		BFT, microalgae(44), probiotics	- less antibiotics (45) - no high investments, adapted to small-scale farms - better water quality, growth & survival	- Probiotics: (46) gives examples of the existing types and their advantages (45) for European Sea Bass - BFT: with pond-based IMTA (shrimp, seaweed, oyster, mullet - Brazil)(47) - Microalgae: positive effects on gilthead seabream(48) & AlgaEnergy (Spain)(49, 50)
D1: Proliferation of pests (e.g. jellyfish)(51), existing and new pathogens(2)	- Temperature rise and other - Decreased disease resistance - Contamination processes	New disease-resistant species	Better growth rate and appearance	Greece: focus on seabass and seabream
		EWS (54), CIS		- Norway: sea lice surveillance program (55) - Scenario (2100): potential oyster herpes outbreak (56)

(more frequent, prevailing, and severe) (45, 52)	(currents, ballast waters, migration of wild species) (53) - Existing, opportunistic organisms become pathogenic (53)	RAS (desinfection & quarantine measures)	Lower contamination risk	
		BFT, microalgae, probiotic	see C1	
	Hypoxia(2)	see A1		
	HAB	see A2		
E1: Increased mortality / mass mortality	Bad water quality:	EWS: - bivalve-based BEWS(57) - apps or web portals for Small and Medium-size Enterprises (SMEs)	- Better informed farming decisions, animal welfare, and profitable farming practices (57)	- France & UK: Sentinel 3, use of satellite data to alert for HAB and water quality deterioration (58) - France: Rephy (59) surveillance program for shellfish - Spain & Greece: observation systems also for extreme weather events (AVRAMAR)(60)
		- Introduction of macrophytes, macroalgae, consuming excess nutrients (N, P, K) - microalgae-assisted aquaculture (61) - shellfish aquaculture to remove nitrogen	- less energy needed for aeration (61) - convert waste into aquafeed (61)	- Greensea in France (15) - Growing interest in Morocco, Algeria and Tunisia - US: shellfish for nitrogen removal (62)
		Integrated Multi-Trophic Aquaculture (IMTA)	- artificial reefs (63) - nutrient cycling (64)	- land-based(65), sea-based(66) & pond-based (47) - Spain: Veta la Palma, land-based IMTA, seabass (67)
		BFT, microalgae, probiotics	see C1	
	Sealevel rise/ Salinity change(2)	Shift to natural or selected saline-tolerant freshwater species or strains(2), euryhaline or marine species(2, 23)		Mediterranean flat coastal lands: shift from finfish/shellfish to shrimp (24) could be interesting for Nile delta
	Hypoxia (33) (2)	see A1		
	Temperature rise	Change farming cycle (6)		- Bangladesh (shrimp): modification of post-larvae procedure for transfer into growing ponds (68) - Greece: change in sea transfer times in marine finfish farming (earlier harvesting) (6)
		Seasonal relocation		Shellfish lines suspended out of lagoon during summer
	Extreme weather events	Shorter production cycle	Meeting the demand of poorer consumers & improving cash flow for farmers	Africa: Nile tilapia, shorter production cycle with higher stocking density(69)
	HAB	see A2		
Example: Mass die-offs of **oyster** larvae in hatcheries	Acidification (70)	- Relocation of production sites - Shift to seaweed farming - Shift of farmed species or strains - Include kelp forest		- Australia: oyster species selection and selective breeding techniques to produce more resistant oysters(71) - US: kelp forest may buffer OA effects on oyster (72)
Adaptation potential for all problems mentioned in this table: (limitations with be discussed more in detail in 2.5)	All the above	**RAS**	- nearly independent of CC impacts - nutrient recycling, waste reduction (73) - controlling water quality	- Egypt (Nil Delta): ponds with intensive units for high-value species(74) - Chile: river shrimp & Rainbow trout, combined with renewable energies, CE & community engagement(73) - France: aquaponic pilot cases Agriloops (75) & Lisaqua (76) - France: test of new types of RAS using IMTA and CE; ex:

				Ricard Foundation (77) (coastal land-based system) - research on the impact of salinity and temperature on marine fish to improve RAS for juveniles(78)
		Relocation (new coastal areas are very limited) **Offshore**	- potential combination with EMR - better water quality - lower pollution influence - less frequent heatwaves (6)	- Spain (offshore): bluefin tuna fattening (minor but lucrative practice in large offshore cages) - Turkey: boom of 'offshore' production of seabass and seabream (79) - Germany, Netherlands, Belgium: combination of MRE with aquaculture (UNITED project) (80)
		Inland/ land-based	- access to nutrient-rich coastal waters - easier access to infrastructure/ communities/ demand potential for local support	- Egypt: a key player in the Mediterranean for inland aquaculture, especially for Nile tilapia (81) - Spain, Esteros: Land-based semi-intensive, extensive finfish productions
		EWS	- warning for extreme weather events - monitoring - surveillance	Extreme weather, destruction of cages: EWS, CIS (82), Monitoring systems (2) For more examples, see other EWS solutions in this table.

Solutions that have been mentioned several times were Early Warning Systems (EWS), RAS, and resiting of facilities. Also, species diversification or genetic strain selection for increased CC tolerance can be emphasized. Increased genetic diversity would also be beneficial for the immune system of the farmed species. However, species diversification by introducing non-native species come also with a risk for invasive species, when they are not produced in RAS systems. Thus, solutions like the ones proposed for B2 should be combined in certain areas to lower the risk of fish escape.

A shift to brackish water and euryhaline species could be an adaptation measure to adapt to increasing saline intrusion and storm surges. Furthermore, high water temperature and increased turbidity call for species that tolerate low dissolved oxygen levels or air-breathing fish (23). For multiple areas of the Mediterranean flat coastal land, a shift from finfish and shellfish farming to shrimp could be envisaged, as this is addressing sea surface temperature warming, submersion risk, and increase of salinity due to rising sea levels (24).

Harmful Algal Blooming (HAB), often caused by nutrient imports through, for instance, the use of fertilizers in agriculture and exacerbated by CC, also affect human health (83). Residues and toxins are accumulating and affecting the flesh quality but could also be detrimental to human health (31). Therefore, the implementation of, for instance, EWS and monitoring systems do come with additional benefits like improved food security (83). Furthermore, these monitoring systems could help to predict storms or changes in water quality by being coupled with, for example, in-situ water samples.

For shellfish farmer, some risks are especially problematic. Shellfish is particular vulnerable to bad water quality and also HAB have a particular severe impact on filter feeding species. Mass die-offs of oyster larvae due to acidification could be a major problem for Mediterranean countries (11). Species that use carbonate for their shells and skeletons will have problems, resulting in slower growth rates, weakened shells and skeletons (84).

At the Lake Victoria in Africa, shortening the production cycle of Nile tilapia in combination with higher cage density was tested, to improve food security, produce intentionally food for the demand for smaller fish of poorer people and increase farmer's cashflows (69). This reduced the exposure of the farmed species to extreme weather events due to the shorter time-to-market and led to higher production volumes in the short term. However, this should not be coupled with increased cage density, as this decreases fish welfare and has severe effects on the immune system.

Benefits for the farmers not mentioned in the table but applicable for all adaptation solutions are risk reduction and limitation of economic losses through addressing the prevailing CC impact. RAS and resiting to offshore areas is further elaborated in Chapter III.C.

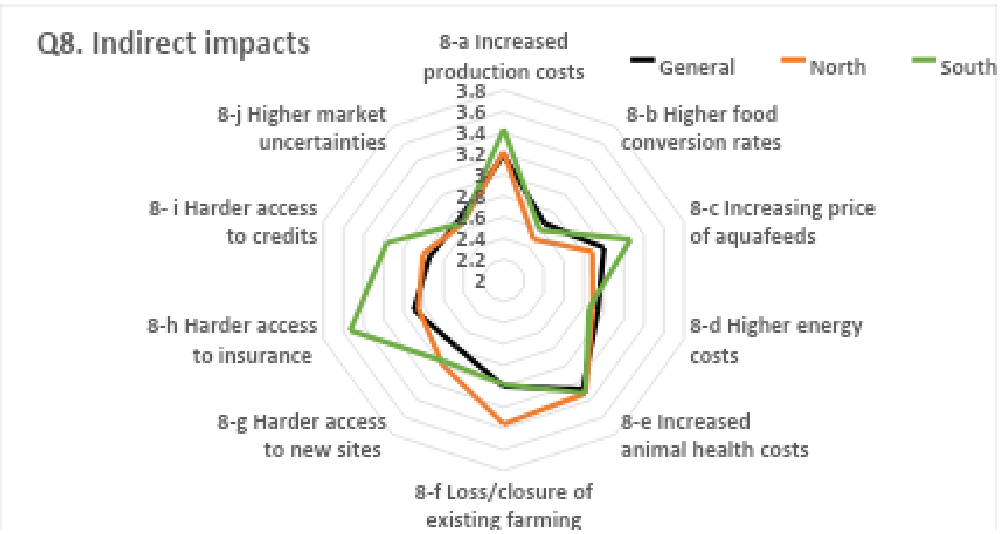
Conclusions on CC impacts

- **Higher summer surface temperatures will at some point exceed the benefit of warmer winter temperatures and become problematic for producing seabream and seabass.**
- **Shellfish have been identified as being severely affected by CC (18, 33), this includes in particular their vulnerability to diseases (53).**
- **Shrimp seem more resilient to warming, salinity, and less food supply than other species like tilapia (24).**
- **In the questionnaire the following direct CC impacts on aquaculture were considered as most concerning (Q7): Water quality deterioration, increased disease frequency and/or severity, emergence of new pathogens, sudden heavy losses due to environmental factors (e.g. anoxia, HAB, storms)**
- **RAS seems nearly independent from CC impacts and is a promising adaptation solution. However, there are still barriers and downsides concerning CC which will be discussed in Chapter 2.5.1**

1. Indirect CC impact on aquaculture and potential benefits resulting from climate action

Indirect impacts were assessed in the questionnaire (Q8). These varied between the Northern and Southern rims. In fact, clear disparities are highlighted in the perception of indirect impacts gathered from the south and the north shores. Tough access to insurance was mentioned as a key concern for participants from the South. The North was more concerned about the loss or closure of existing sites. Increasing aquafeed prices, production and health costs were concerning indirect impacts of CC and were mentioned by nearly all participants. Therefore, cost-effective solutions should be found that take as well into account higher fluctuating feed prices. Aquafeeds are responsible for about 50-80% of total production cost for high-value species in intensive farming facilities and are a major limiting factor of fed-aquaculture sustainability (85). Especially for species like Nile tilapia, which account among others for the largest proportion of aquafeeds, feeding practices have to continuously be modified and adapted (86). At the same time, aquafeed hold an immense potential for GHG emission reduction. Here the replacement of fish meal and fish oil with low trophic and plant-based ingredients is targeted. Since Nile tilapia accepts artificial feeds immediately after yolk-sac absorption and is 98% vegetarian, aquafeeds with a high ratio of plant-based proteins are possible (74). Among the candidates of novel ingredients for aquafeeds, the following look the most promising: insect meals, macro- and microalgae, and Single-Cell Ingredients (SCI) (87). However, for all these new materials, there remain knowledge gaps of their nutritional value for aquaculture or sustainable mass production means, which also have to be adapted to the local context and the specific species requirements. An example can be found in the use of macroalgae which are incorporated as additives in aquafeeds for critical rearing conditions as proposed by a French feed additive company Olmix (88). Another project is focusing on using diets with mussel meal (89) or discarded biomass (90) for Gilthead seabream in Spain.

Figure 4. Indirect CC impacts on aquaculture mentioned in the questionnaire



A solution to address the decreased availability of terrestrial fertile soil for aquafeeds or limited water availability is integrated farming or so-called aquaponics. Despite the need to supplement the fish's diet, additional benefits of aquaponic systems could be nutrient recycling, waste reduction, and energy footprint minimization, following a circular economy approach (91). For flathead mullet (26) and rainbow trout (92), RAS systems in combination with aquaponic are currently being researched.

Increased animal health costs are another key indirect CC impact mentioned by the participants in the questionnaires (Q8). The weakened immune system of the farmed species could be counteracted by for instance improving animal welfare, high-quality aquafeeds, EWS, and diversification of more tolerant species or species strains. All this would be linked to increased costs or initial investments in the short term. However, considering the existing and increasing risks already today, and more severe for the mid-and long-term, these investments seem reasonable and could become a competitive advantage and contribute to cost-efficiency in the long run.

Conclusions on indirects CC impacts

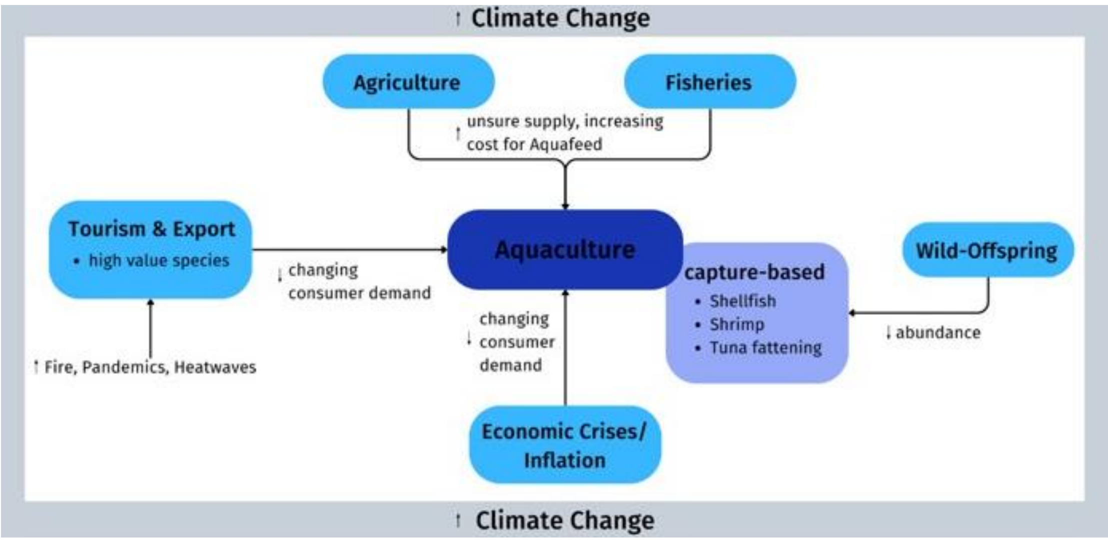
- **Most concerning indirect impacts are: increased production costs, increasing price of aquafeeds, increased animal health costs, loss/closure of existing farming sites (North), and harder access to insurance (South) (Q8)**

2. Overlaps with other sectors affecting aquaculture

As CC is a global phenomenon, other sectors that are linked to aquaculture are also impacted. Some of these interactions are illustrated in Figure 5.

- Shortages in agricultural production and fisheries due to CC, could lead to an unsure aquafeed supply and increased costs (2, 34). This aligns with the expectations mentioned in (Q8). Species with broad-based feeding strategies may be less vulnerable to these impacts than those with a narrow diet (23).
- Species like Flathead grey mullet depend mainly on wild fry. A reduction due to CC would, thus, lead to expansion limitations and could become problematic (7). Species not dependent on wild fry seem to be more reliable and less vulnerable (23).
- CC impacts like fires, heatwaves, and pandemics significantly impact the tourism and export sector for high-value species, as this leads to lower demand for these goods (17). This underlines again the importance of adapting aquaculture in a way that its resilience is ensured.

Figure 5. Exemplary sectors impacted by climate change and affecting aquaculture, based on (34, 2, 17)



3. Impacts of Mediterranean Aquaculture on CC

Instead of accelerating climate change and aggravating the situation, aquaculture farms can potentially **mitigate** CC through their daily activities. This would increase their future viability and resilience, contributing to one of the most pressing issues of the 21st century. Therefore, this chapter identifies opportunities for the aquacultural sector to mitigate CC and create additional benefits for themselves and/or society.

Greenhouse Gas (GHG) emissions resulting from marine finfish farming production in the Mediterranean were rapidly extrapolated from (93) based upon the ratio of productions/ GHG emissions. They vary around 2.7 million tonnes of GHG per year, while emissions due to shellfish production would not exceed 0.2 million tonnes. Thus, from a CC mitigating perspective, a shift to **low trophic aquaculture with shellfish and algae** could be recommended to increase ecosystem services such as carbon sequestration (94–96, 38, 86, 97). Additionally, mussels and clams were described in several studies as a potential carbon sink with a net carbon capture capacity of 233 and 91 g CO_2/kg of fresh product, which makes bivalve aquaculture an opportunity to being a net carbon sink and potentially useful in carbon trading systems. Nevertheless, this needs further research like it is currently been conducted in Spain (90) and farming emissions have to be equally taken into account to assess the potential GHG emissions of bivalve aquaculture.

An advantage of shellfish farming would be their potential as sentinels for CC and biodiversity as Biological Early Warning Systems (**BEWS**). Shellfish animals are considered bioindicator species due to their high environmental sensitivity. Therefore, their biological responses are environmental-dependent and directly observable. Especially, oysters farms are proposed as sentinels of climate variability and CC in coastal ecosystems (98). In this way, aquaculture systems could be acting as an EWS itself for CC monitoring in coastal areas (99). For such win-win relationships, a high level of cooperation and integration of the participating actors is needed (2).

In this regard, another approach seems very promising to combine with lower trophic aquaculture as seaweed and mussel farms. The **combination with windparcs** has been explored by Maar et al. (2023) in Denmark. They calculated that the total carbon captured and harvested from seaweed biomass and mussel shells from these systems would equal 40% of the carbon dioxide emissions from the Danish agricultural sector (97). However, environmental impacts of offshore renewable energy (ORE) still require further research. In any case, if seaweed farming is seen as a blue carbon opportunity, it has to be designed following the guidance of the Ecosystem Approach for Aquaculture (EAA) (100). The EAA describes a method of how these projects should be implemented. Elements like stakeholder integration for sustainable development, equity, and resilience of interlinked social-ecological systems are essential for the success of the EAA project (101)

Other projects tested are Aquavoltaics with Floating Photovoltaic (FPV)(AquaPV) on freshwater areas in Croatia (102). The combination of **ORE**, which provides off-grid potential, and aquaculture has been elaborated as an approach to reduce costs for RE. GEPS Technology works together with several sectors to provide ORE directly where it is needed, based on solar, wave, or wind power (103). This offshore energy could then be used for feeder machines, fridges, or aeration systems. Other projects like the EU project Olamur combine wind parks with low-trophic aquaculture (104, 97). However, the ORE and their combination with aquaculture is still in the pilot stage and needs to be accompanied by further research (105). In general, the combination of land-based aquaculture with already mature RE like solar energy holds major GHG emission reduction potential (106). This is done on facilities in Spain by AVRAMAR with production systems for seabass and seabream (60).

As habitat degradation largely impacts and is impacted by the aquacultural sector, Integrated Multi-Trophic Aquaculture (**IMTA**) could be used to adapt as well as mitigate CC effects. One example is an IMTA project in Italy, which includes underwater gardens, strong bioremediation activity, and biodiversity increase to restore ecosystem services (107). IMTA, showcases nutrient recycling, as observed in projects in Brazil growing aquatic plants in fish farm effluent ponds. Another best practice example is the farm Veta la Palma in Spain, which focuses mainly on seabass production while following a land-based IMTA approach (67). This model has been described as a dual-purpose design for both aquaculture and conservation. It shows how aquaculture can be used as the economic driver to reconstruct and restore wetlands and reinstate the hydrology needed to redress the loss of wetlands, while also producing added value due to their high quality and ecological sustainability credentials (108). Despite the complexity of this approach and the implementation challenges, the professionals asked in the questionnaire mentioned to be very keen to try out the IMTA approach (Q14). As this approach is recommended by several international institutions and more and more mentioned by practitioners, this is an approach to be kept in mind and to develop further in the future.

A large part of the aquacultural sector still relies on fossil fuel energy use. The energy input in the production and feed delivery for semi-intensive and intensive systems is around 0 – 3 kWh/kg (106). To be able to reduce GHG emissions and shift energy use of a farm it is important to have an idea about the farm's emission and consumption patterns. A common method to assess the energy use, carbon footprint, and potential for GHG emission reduction is a Life Cycle Assessment (LCA) (109). This has been conducted, for instance, by AVRAMAR (60) or for seabass and seabream production in the Mediterranean in (110). LCAs demonstrated that energy dependence increases with increased aquaculture production intensity (111).

One key activity to reduce GHG emissions in aquaculture is the modification of vessels used to run farms (112). These could be shifted to carbon-neutral vessels or cleaner energy types like renewable energies or low-carbon fuels while increasing energy efficiency or a shift to digitalized farming, where fewer human interventions are needed. One example is the new electric-powered shellfish vessels in France south of Brittany for oyster farms (113).

In general, it is recommended to adopt a circular economy approach by, for example, utilizing fisheries by-products in aquafeeds to recycling fish effluents and shells in various treatments or reuse fish waste for textile production (114), in this way economic income diversification is practiced and costs could be reduced.

In conclusion, plenty of CC mitigating solutions for aquaculture already exist. However, many of them are still in the research and development stage and are not yet ready for industrial scaling. The integration of aquaculture professionals in this stage is essential, as this helps to direct the development of these approaches to be applicable and relevant for the practitioners and amplify implementation behavior at a later stage. Innovations at early development stages come with implementation risks closely related to transferability, replicability, and efficiency. However, they also hold opportunities for income diversification and creating a competitive advantage in the sector.

Most promising CC mitigation actions for Mediterranean aquaculture

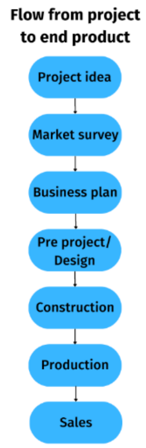
- **Shift to lower trophic aquaculture for GHG reduction and food security. This comes with the possibility of entering the carbon trading market or combining (offshore) renewable energy to reduce operation costs.**
- **LCA is a common method for GHG emissions assessment, and vessels have been identified as major GHG emittants.**
- **High-quality aquafeeds are important for animal welfare, and plant-derived substitutes should be prioritized to reduce environmental impacts.**
- **A higher level of intensification leads to higher energy dependence.**
- **Higher energy dependence should be accompanied by RE, at least for land-based facilities (mature technology). This should help climate mitigation and enhance independence from market-energy prices.**

C. Solutions to address specific vulnerability issues due to CC

The General Fisheries Commission for the Mediterranean (GFCM) of the Food and Agriculture Organization of the United Nations (FAO) has launched three Aquaculture Demonstrative Centres (ADCs) showcasing best practices, educational programs, and hands-on technical support. Two of them are in the Blacksea focusing on shellfish in Romania and finfish in Türkiye. The first Mediterranean one is placed in Egypt and focuses on brackish water aquaculture and a fourth is planned to be installed in Tunisia focusing on offshore cage farming and environmental monitoring (115). The following proposed solutions and best practices attempt to combine the key themes of these ADCs with the analysis conducted in this report to support ambitious but applicable climate adaptation actions.

1. Solution 1: Recirculating aquaculture system (RAS)

RAS technologies are predicted to be the most employed production system in the world, reaching more than 40% in 2030 of the total aquaculture farm systems worldwide (116).



Problem addressed by RAS:

- major adaptation solution to reduce exposure to climatic extremes (2)
- independent of numerous climate impacts
- parameters like water quality, including temperature, DO, salinity, and pH can be controlled (2), which allows for better growth and reproduction control
- reduced need for freshwater, while maintaining a healthy environment for fish (117) (2)

Steps for Implementation/ Major issues to be addressed before launch (118)[5]:

1. Sales prices and market for the fish in question
2. Site selection including licences from authorities
3. System design and production technology
4. Workforce including a committed manager
5. Financing the complete project to a running business

Benefits for aquaculture farmer:

- Stable production
- Easy to adapt conditions
- Disease treatment and control

Positive impacts on society or environment:

- Food production (relative secure)
- Food production close to consumption place
- No significant effects on habitat destruction, water pollution, eutrophication, or species escape (117)

Limiting factors:

! Technical expertise is needed (119)

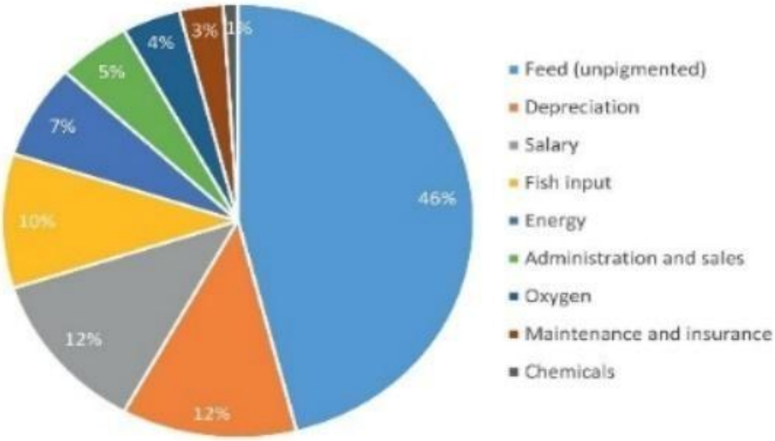
! High initial investment and operational costs (119) operations highly sensitive to market price and input costs (especially for feed and energy) (119, 117)

! Increasing energy dependence with increasing intensification (111)

! GHG emissions (117)

[5] More detailed information can be found in (118)

Figure 6. Example of cost distribution of a large farm for portion sized trout (2 000 tonnes/year) taking in fingerlings and growing them to 300-500 grams. Total production cost per kilo live fish produced is less than 2 EUR per kg. The total investment cost for such a fully recirculation in-house system is around 4 EUR per kg production (total 8 mio. EUR) (118)



Call for combination with RE and potentially aquaponic to reduce market-related dependency on feed and energy input costs!

Best Practice Example: RAS with RE in Chile (73)

This Best Practice Example in Chile focuses on two species. On the one hand, there is **River Shrimp**. For the Mediterranean flat coastal lands, a shift from finfish and shellfish to shrimp farming was proposed due to better tolerance to salinity, temperature increase, and submersion risk (24). RAS are not significantly affected by CC impacts like salinity intrusion, which is a major advantage of this system (117). However, they could be used for nursery production of juveniles before their transfer to on-growing production systems that do get impacted by salt intrusion.

The second species is **Rainbow trout.** This species accounts for over 50% of the Mediterranean freshwater aquaculture production, which is of particular importance in Egpyt. Therefore, this example was chosen to gain useful insights, which seem very applicable and relevant, especially for the SEMCs.

The combination of aquaculture with RE has been identified in Chapter 3 as a key adaptation and mitigation possibility. As RAS is a great climate adaptation solution, it does increase energy dependencies and GHG emissions. Therefore, the combination with RE addresses these limiting factors.

This farm in Chile combines the following three parts:

RAS + Solar Water Treatment System (SWTS) + Photovoltaic Plan System (see Figure 7)

Guiding principles (73):

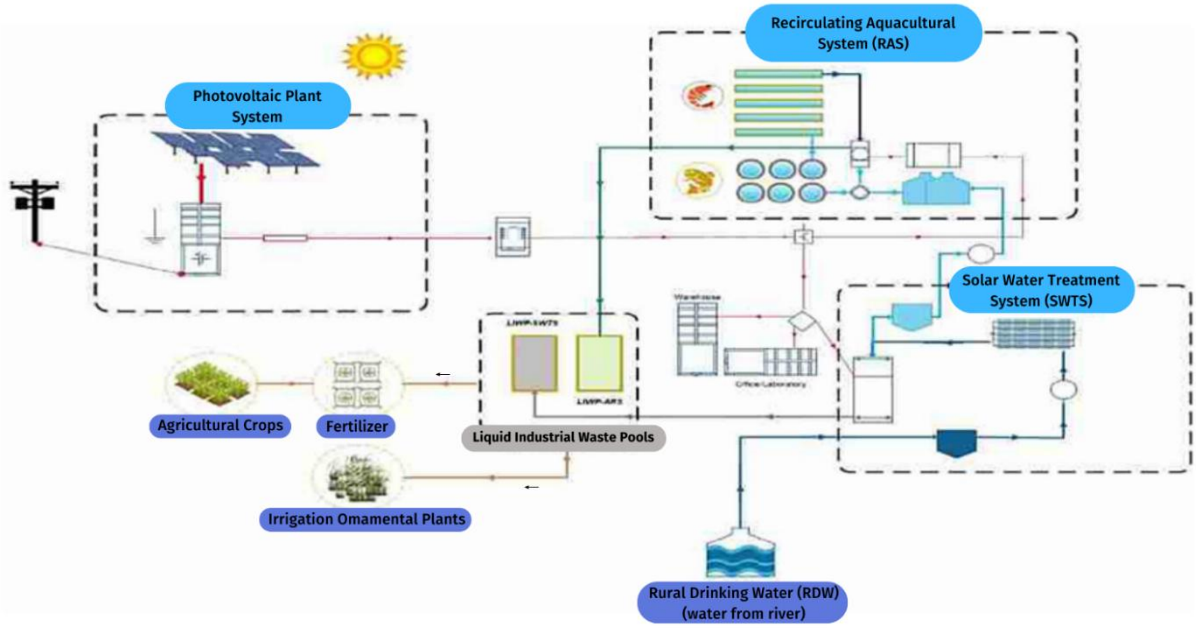
i. Co-construction: integrating local community
ii. Promoting the river shrimp farming in RAS,
iii. Water obtained through the treatment system allows a **regulated and limited water consumption**
iv. Use of solar energy for the production of electrical energy

Mitigation impacts: GHG reduction, reuse of liquid waste, sludge for irrigation and as fertilizers => Following a Circular Economy approach

Farmer benefits: Added value and income diversification due to the production of agriculture fertilizers from RAS waste and the sale of trout and shrimp (73).

Promising application regions: In Egypt (Nil Delta) several ponds with intensive units for high-value species do already exist, as large parts of the aquacultural production are expected to move further to the desert region (74). Therefore, a combination with solar energy could be beneficial.

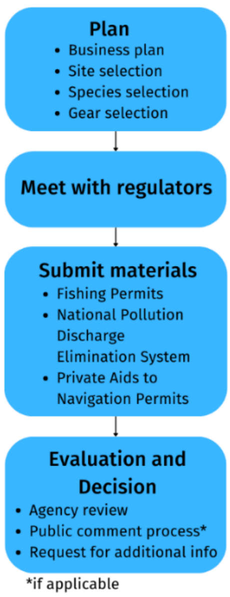
Figure 7. Best Practice Example of RAS coupled with RE in Chile (73)



2. Solution 2: Re-siting to offshore locations

Re-siting farms to areas with more suitable conditions or higher tolerance to CC is one of the most obvious CC adaptation solutions for aquaculture. Moving inland or offshore remains the main possibility for the Mediterranean basin, as other coastal areas are scarce (120). As inland aquaculture is often done in RAS systems, which is described in more detail in Chapter III.C.1, this part will focus on relocation possibilities to offshore sites.[6]

Figure 8. Exampletory permitting process for offshore aquaculture in the US



[6] More information on high-value species offshore aquaculture can be found in the appendix in Annex II.

Problem addressed:

- Potential better environmental conditions (temperature, salinity, HAB, extreme weather events) (23)
- CC impacts in coastal areas are relatively dramatic
- Pollution from tourism

Steps to implement:

Key steps in the permitting process for aquaculture are illustrated exemplarily in Figure *8*. This is derived from NOAA for the US Pacific Islands region in the federal context (121) to give an overall idea of the process, but still has to be adapted to the Mediterranean context.

Benefits for farmers:

- Potential for more stable water conditions, better water quality (122)
- Some farms could identify production increase due to better conditions (122)
- Fewer heatwaves

Positive impacts on society or environment: Environmental outputs and impacts of the aquaculture farms are less severe due to a dilution effect of the effluents (120). In some cases inshore water quality improved after the relocation of farms to offshore areas, which resulted in fewer conflicts with other sectors (122).

Limiting factors:

! Site identification still needs local conditions assessments; this is often relatively complicated and needs support from government bodies

! Space limitations also in offshore context (MSP) and potentially higher GHG emissions due to longer transport ways for monitoring/ operating activities

! Offshore conditions vary in different areas, e.g. in some offshore regions the occurrence of HAB may be higher in comparison to coastal areas (2)

Potential application regions: In the Mediterranean basin there are currently nearly no significant commercial offshore aquaculture activities if Turkish finfish farms are not considered "offshore aquaculture" (122).[7] However, considering the limited place in coastal areas and higher human pressures such as coastal pollution, the offshore sector remains an interesting adaptation solution for the entire Mediterranean region.

Best practice example: Coupling low trophic offshore aquaculture with ORE

The aquaculture sector is not the only strongly growing sector. In Europe as well as in the Mediterranean region a high increase in Renewable Energy (RE) is predicted. Considering limited place availability on land, offshore possibilities are equally taken into account.

Co-locating offshore wind farms with low trophic aquaculture (LTA) is often seen as an attractive and efficient multi-use strategy (97) to find synergies between different sectors and cost reductions. On the one hand, the artificial reef effects of offshore renewable energy and LTA could result in restorative ecosystem services. On the other hand, offshore aquaculture could reduce operating costs for the two sectors and provide nutritious seafood. A conceptualization of how this could look is displayed in Figure 9.

Several environmental risks depend on the aquacultural type whether it is fed, unfed, or autotrophic aquaculture. Benthic impacts are higher for fed and unfed species, water column pollution is higher for fed, and food and nutrient depletion in water collums is higher for unfed and autotrophic. Disease Outbreaks and Marine Mammal Interactions are very similar for all aquacultural types (123). Different risk reduction approaches for these environmental risks are presented in (123).

Low trophic aquaculture could be beneficial for CC mitigation, carbon sequestration, and aquaculture restoration with for instance sugar kelp or mussel farming (120). This is currently being tested in the UNITED project from the

[7] In Turkey aquaculture activities in waters with more than >40m depth is considered as offshore aquaculture, which could still be in the first nautical mile from shore (79). In other countries, this could still be considered as inshore mariculture (120).

EU in Germany with blue mussels and seaweed or Belgium with flat oyster (80). Similar projects are expected to be also applicable to the Mediterranean basin.

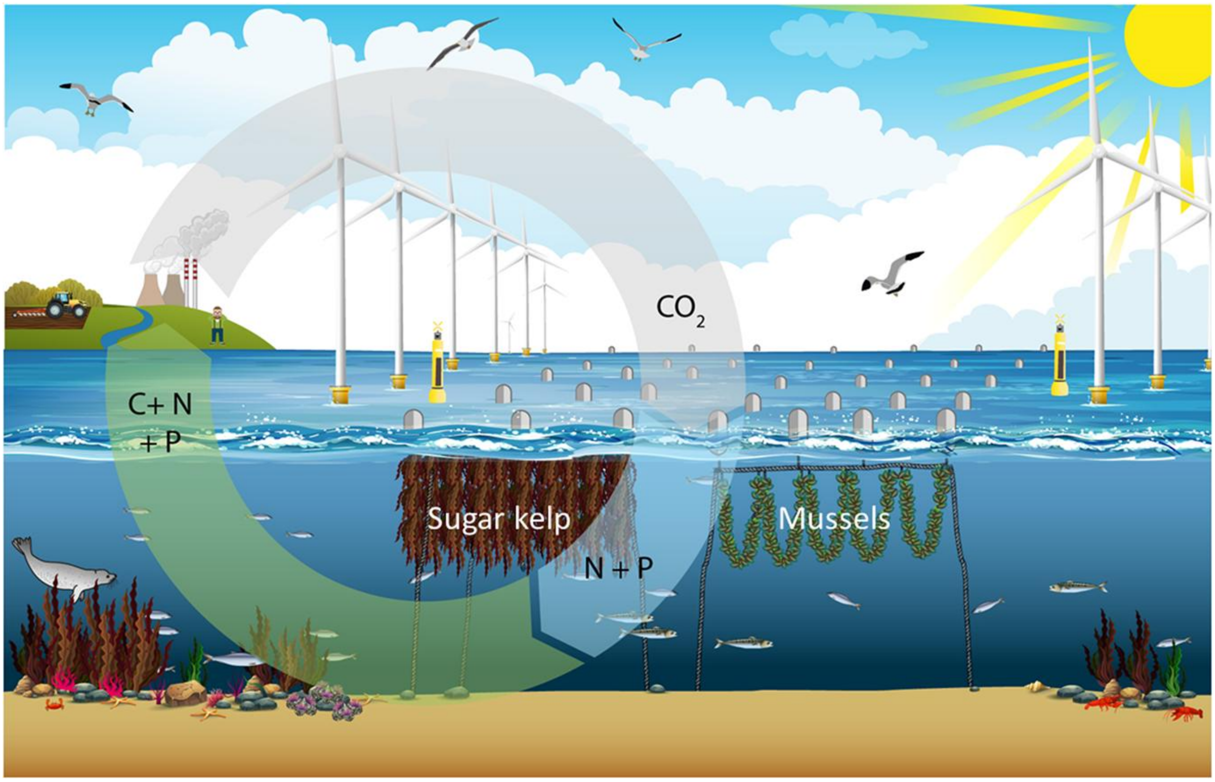
Benefits for farmers:

- shared operational costs between RE and aquaculture sector (97)
- Potential for income diversification

Positive impacts on society or environment:

- deliver emission-free energy, nutritious seafood, and positive ecosystem services through emission (CO2 and nutrients) capture and utilization (97)
- potential artificial reef effect (124)

Figure 9. Conceptual figure of multi-use combining offshore wind farms with low trophic aquaculture (97)



IV. Barriers and related enablers needed to implement these solutions

In the following financial and regulatory enablers for aquaculture's CC adaptation will be elaborated.

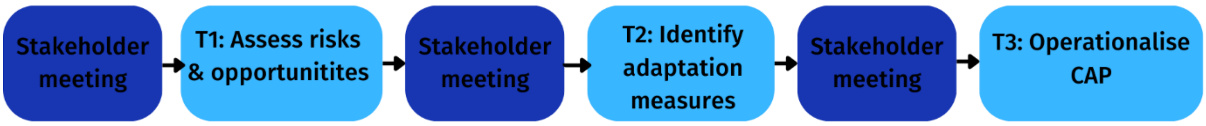
Financial enablers:

Access to credits and insurance is essential to facilitate the sustainable development of aquaculture in the Mediterranean (2). Especially for the so-called Global South, participants of the questionnaire labeled the harder access to insurance as a highly concerning key indirect CC impact (Q8) and a major challenge to address. Therefore, assurance support for CC risk-related aquaculture needs to be developed.

Regulatory enablers:

A promising regulative enabler could be the inclusion of Climate Adaptation Plans (CAP) or Climate Smart Aquaculture (CSA)[8] in the National Adaptation Program of Actions (NAPA) (2, 125). CSA applied in aquaculture include IMTA, selection of CC-tolerant genetic strains and species, or increased RAS to reduce the need for freshwater (2). This could result in an overarching strategy within a country to address CC and its impacts on the aquaculture sector (2). This approach termed CAP by the EU (18, 126), stresses stakeholder participation, and combines bottom-up and top-down approaches (33).[9]

Figure 10. Simplified guidelines for developing a CAP with three key tasks (T1-3), based on Pham et al. (2021)



CSA/CAP can improve regional vulnerability assessments and provide specific site and species recommendations, which is currently lacking and is unlikely to be solely done by farmers. In this way, adaptive capacity and resilience would be strengthened, and thus vulnerability to CC effects reduced. The UNDP's CSA toolkit for Malawi could be synthesized and adapted to an action-oriented toolkit for Mediterranean countries and included in the NAPA, as proposed among others by the FAO (2, 125). CSA promotes sustainable aquaculture investments (125) and helps farmers make informed sustainability and adaptation choices. Training modules for practitioners, as in Bangladesh (82), and in Vietnam (127), should accompany these efforts (128).

The Mediterranean coast is object to several pressures and usages. Marine Spatial Planning (MSP) and Integrated Coastal Zone Management (ICZM) are gaining increasing attention. Another approach, that directly addresses aquaculture is the "Allocation Zone for Aquaculture" (**AZA**). AZA are suitable marine areas for aquaculture, where aquaculture is prioritized over other marine activities, and where interferences are minimized or avoided (129). This approach could allow for active integration of aquaculture in MSP and ICZM and steer the development of aquaculture toward sustainable management (11).[10]

[8] CSA is defined as "aquaculture that sustainably increases productivity, resilience (adaptation), reduces/removes greenhouse gases (mitigation), and enhances the achievement of national food security and development goals" (125).

[9] More information about key principles and particular steps of CSA/CAP approach can be derived from Pham *et al.* (2021).

[10] An example could be the AZA in Gulluk Bay in Turkey (137).

V. Outlook into future research needs and projects

The urgency to adapt the aquaculture sector to CC is widely acknowledged. Several adaptation actions can and should be initiated and implemented by farmers as soon as possible. However, many solutions need further development and scientific support.

- Local vulnerability and site suitability assessments, function as enablers for climate adaptation and are needed by farmers (Q15). The best practices mentioned like the planning tool for Palau, could be modified for and applied in the Mediterranean (20, 19, 21). The development of such tools requires support from governmental bodies, external funding and should be done in an integrative and systematic manner, considering multiple challenges (e.g. governance, market systems, financing).
- Strengthen bilateral and multilateral cooperation in the Mediterranean, increasingly involving the European Union and international public and private networks of experts (FAO, GFCM, SIPAM, EATIP, EUROfish Organization, etc.), actively involved in the sustainable development of aquaculture, is essential to enhance its resilience to climate change. Regional-multinational workshops for different aquaculture types (freshwater, brackish, and marine water) can help to assess shared risks, address farmers' problems, and exchange best practices. Existing aquaculture demonstrative centers (ADCs) could host workshops and lead a more integrated role in the sustainable development of Mediterranean aquaculture. The workshop's results could then be shared as guidelines and may be integrated into national CAP/CSA.
- While CC impacts challenge the aquaculture sector with adaptation and mitigation demands, they also present an opportunity to reshape Mediterranean aquaculture. Potential areas for further investigation include market diversification, cost-efficiency improvements, or combination with ORE.

VI. Recommendations and final conclusions

This study gives an overview of Mediterranean aquaculture's vulnerability to CC and identifies ways in which farmers can adapt to and mitigate these CC impacts. Additional local vulnerability assessments are essential to address the specific needs of individual farms and species. Nevertheless, this study supports and empowers farmers to shift to more sustainable and resilient aquacultural practices for the main farmed species and production systems in the Mediterranean.

With regards to NMCs' and SEMCs' socio-economic contexts and associated productions, operational and strategical recommendations should be adapted to these contexts. Thus, farms focussing on high-value species could adapt, for instance, land-based **IMTA** systems like Veta la Palma in Spain, which follow a dual approach of aquacultural production of high-value species like seabass and conservation efforts. This best practice example showcases how a profitable productive aquacultural system could be used to restore ecosystem functions and services (67).

For food security, **low trophic aquaculture** is recommended to maximize the energy output from ecosystems. A shorter time-to-market, as it has been tested at Lake Victoria, could reduce the risk of extreme weather event exposure and increase food security (69). However, this should not be coupled with higher cage density to accommodate for the already increased risk of disease outbreaks due to CC and to support fish welfare.

Improving **fish welfare** is seen as the being possibly the most cost-efficient intervention for mitigating the disease risk in the context of CC. The increased risk for diseases due to CC was one major concern mentioned in the questionnaire (Q7). Thus, stress and overcrowding should be avoided, as well as high-quality feeds should be applied, as this can significantly improve fish tolerance against certain disease outbreaks (10). These aquafeeds could include for instance microalgae or probiotics. The production of microalgae for human consumption or as an additive for aquafeed has been mentioned as a promising opportunity for CC mitigation (130, 131).

Re-siting aquaculture production facilities based on region-specific analysis and models that integrate multiple dimensions linked to CC (e.g. storm) or other human activities can facilitate climate adaptation (6)(132). Offshore and inland aquaculture with RAS systems, are promising options and developed in detail in chapter 3.4. Especially **RAS** is already applied at a commercial scale and is expected to have a major development in the upcoming years. As production intensification comes with a higher energy dependence, a combination with RE should be explored.

Major commercial species for the Mediterranean like European seabass and Gilthead seabream have been assessed. Meagre could present an alternative species due to its higher temperature tolerance and shorter time-to-market, which reduces the risk of exposure to extreme weather events (6). Shrimp is more resilient against warming, saltwater intrusion, and reduced fish feed supply in fresh- and brackishwater aquaculture than Nile tilapia, carp and catfish (24).

The increasing risk of (new) disease outbreaks due to CC has been mentioned by the participants of the questionnaire as a major concern (Q7). Gradual **diversification** of production to more heat-tolerant species and resilient genetic strains is recommended (10). Investments in new prevention and treatment tools are crucial despite regulatory challenges in their licensing process (10).

EWS and smart aquaculture approaches, help to predict changes in water quality or upcoming extreme weather events. This enables informed management decisions at an early stage and supports disease control, especially for offshore aquaculture (10).

Final conclusion:

- **Fish welfare and shift to CC-tolerant species and genetic strains are important for a strong immune system to counteract disease outbreaks.**
- **Resiting to offshore or inland in combination with RAS could be a widespread adaptation solution.**
- **Low trophic aquaculture should be prioritized in human consumption and utilization in aquafeeds regarding current sustainability constraints and supply options (86).**

- **EWS for analyzing and monitoring diseases, HAB, and potential extreme weather events are essential for the adaptation of the Mediterranean aquaculture sector.**
- **Local vulnerability assessments and recommendations for site suitability are major enablers for adaptation measures on the farm level.**

VII. Literature Cited

1. Handisyde N, Telfer TC, Ross LG. Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. Fish and Fisheries 2017; 18(3):466–88.
2. Barange M, Bahri T, Beveridge M, Cochrane KL, Funge-Smith S, Poulain F et al. Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options 2018.
3. Intergovernmental Panel on Climate Change. Working Group. Climate change 2001: Impacts, adaptation and vulnerability ; contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. 1. publ. Cambridge, UK, New York: Cambridge University Press; 2001.
4. FAO. The State of World Fisheries and Aquaculture 2024. FAO; 2024.
5. FAO. The State of Mediterranean and Black Sea Fisheries 2023. FAO; 2023.
6. Stavrakidis-Zachou O, Lika K, Anastasiadis P, Papandroulakis N. Projecting climate change impacts on Mediterranean finfish production: a case study in Greece. Climatic Change 2021; 165(3-4).
7. Carvalho N, Guillen J. Aquaculture in the Mediterranean. In: IEMed. Mediterranean Yearbook 2021. p. 276–81.
8. Sadek S, Elewa A, Ahmed N, Munir S, Mahfouz AR, Nasr-Allah A. An assessment and analytical report for integrated agriculture-aquaculture (IAA) systems in Egypt 2023.
9. Rosa R, Marques A, Nunes ML. Impact of climate change in Mediterranean aquaculture. Reviews in Aquaculture 2012; 4(3):163–77.
10. *Cascarano MC, Stavrakidis-Zachou O, Mladineo I, Thompson KD, Papandroulakis N, Katharios P. Mediterranean Aquaculture in a Changing Climate: Temperature Effects on Pathogens and Diseases of Three Farmed Fish Species. Pathogens 2021; 10(9).*
11. *Farahmand S, Cinar EM, Safa A, Lam V, Djoundourian S, Shahin W et al. Climate Change Impacts on Mediterranean Fisheries: A Risk and Vulnerability Analysis for Main Commercial Species. SSRN Journal 2022.*
12. *FAO. Aquaculture statistics | Groupe de travail chargé de coordonner les statistiques des pêches (CWP); 2024 [cited 2024 Jun 10]. Available from: URL: https://www.fao.org/cwp-on-fishery-statistics/handbook/aquaculture-statistics/fr/.*
13. *Plan Bleu. Aquaculture en Méditerranée; 2021 [cited 2024 Jun 26]. Available from: URL: https://planbleu.org/page-theme/aquaculture/.*
14. *Bolognini L, Grati F, Marino G, Punzo E, Scanu M, Torres C et al. Safeguarding Marine Protected Areas in the growing Mediterranean Blue Economy: Recommendations for aquaculture | EU Aquaculture Assistance Mechanism 2019.*
15. *Greensea. Greensea Marine Biotechnologies; 2024 [cited 2024 Jun 28]. Available from: URL: https://en.greensea-all.com/.*
16. *Masi M, Di Pasquale J, Vecchio Y, Pauselli G, Tribilustova E, Adinolfi F. A cross-sectional study in Mediterranean European countries to support stakeholders in addressing future market demands: Consumption of farmed fish products. 2352-5134 2022; 24:101133. Available from: URL: https://www.sciencedirect.com/science/article/pii/s2352513422001296.*
17. *Sarà G, Mangano MC, Berlino M, Corbari L, Lucchese M, Milisenda G et al. The Synergistic Impacts of Anthropogenic Stressors and COVID-19 on Aquaculture: A Current Global Perspective. Reviews in Fisheries Science & Aquaculture 2022; 30(1):123–35.*
18. *AAM. Climate-Change adaptation in the aquaculture sector, in: Mechanism, A.A. (Ed.), Guidance document (Draft). European Commission. Brussels. 2023.*
19. *NASA. NASA Satellites Help Plan Future for Palau Fish Stocks; 2023 [cited 2024 Jun 26].*
20. *MacKay J. Protecting Palau's Food Security and Marine Ecology Using Satellite Technology. Scientia 2021.*
21. *The Nature Conservancy. Palau Aquaculture Suitability; 2024 [cited 2024 Jun 26]. Available from: URL: https://www.maps.tnc.org/palau-aquaculture/#/.*
22. *Haberle I, Hackenberger DK, Djerdj T, Bavčević L, Geček S, Hackenberger BK et al. Effects of climate change on gilthead seabream aquaculture in the Mediterranean. 0044-8486 2024; 578:740052. Available from: URL: https://www.sciencedirect.com/science/article/pii/S0044848623008268.*
23. *Harvey B, Soto D, Carolsfeld J, Beveridge M, Bartley DM. Planning for aquaculture diversification: the importance of climate change and other drivers. FAO 2017.*
24. *Nadarajah S, Eide A. Are Asian fresh and brackish water aquaculture production vulnerable or resilient towards climate change impacts? Aquaculture Economics & Management 2020; 24(3):232–54.*
25. *Shen Y, You W, Luo X, Lu Y, Huang M, Ke C. An overview of the mechanisms underlying hypoxia tolerance differences in aquatic animals and their inspirations for aquaculture. Rev Fish Biol Fisheries 2023; 33(4):1223–36.*
26. *Gisbert E, Molas S, Hernández E, Carbó R, Ruiz A. Production of Flathead Grey Mullet (Mugil cephalus) and Lettuce (Lactuca sativa) in a Coupled Aquaponic System under Suboptimal Water Temperatures. Fishes 2024; 9(6):189.*
27. *Pita I, Mouillot D, Moullec F, Shin Y-J. Contrasted patterns in climate change risk for Mediterranean fisheries. Glob Chang Biol 2021; 27(22):5920–33.*
28. *Brander KM. Global fish production and climate change. PNAS 2007.*
29. *Nugroho PNA, Mustaghfirin MA, Pambudi DSA, Imron A, Aminudin MR, Wulandari DA. Optimization of Paddle Wheel Aeration, a preliminary study of Integrated Smart Aquaculture System. J. Phys.: Conf. Ser. 2021; 2117(1):12032.*

30. Ramesh P, Jasmin A, Tanveer M, U RR, Ganeshan P, Rajendran K et al. Optimizing aeration efficiency and forecasting dissolved oxygen in brackish water aquaculture: Insights from paddle wheel aerator. Journal of the Taiwan Institute of Chemical Engineers 2024; 156:105353. Available from: URL: https://www.sciencedirect.com/science/article/pii/S1876107024000129.
31. Ajmal T, Mohammed F, Goodchild MS, Vinu Padman JS, Halse S. Mitigating the Impact of Harmful Algal Blooms on Aquaculture. Abagold: A Case Study; 2024.
32. King JH. Health Communication Blindspot: A Case Study of Harmful Algal Blooms in the South (HABITS).
33. Peck MA, Catalán IA, Damalas D, Elliott M, Ferreira JG, Hamon KG et al. Climate change and European Fisheries and Aquaculture: 'CERES' Project Synthesis Report; 2020.
34. Le Gouvello R, Simard F. Durabilité des aliments pour le poisson en aquaculture. Available from: URL: https://policycommons.net/artifacts/1372998/durabilite-des-aliments-pour-le-poisson-en-aquaculture/1987210/.
35. Steeves LE, Filgueira R, Guyondet T, Chassé J, Comeau L. Past, Present, and Future: Performance of Two Bivalve Species Under Changing Environmental Conditions. Front. Mar. Sci. 2018; 5.
36. La Voix de l'Ain. Pisciculture dans la Dombes : l'élevage de crevettes en projet. HCR 2023 Aug 7 [cited 2024 Jul 1]. Available from: URL: https://www.lavoixdelain.fr/pisciculture-dans-la-dombes-lelevage-de-crevettes-en-projet/#.
37. Salicornes et Crevette Impériale des marais Charentais. La crevette impériale des marais charentais.; 2016 [cited 2024 Jul 1]. Available from: URL: http://www.crevettesimperiales.fr/PageCrevetteActu2.php.
38. Fredriksson O. Farming The Food Chain | Low Trophic Aquaculture; 2021 [cited 2024 Jul 1]. Available from: URL: https://www.foodunfolded.com/article/low-trophic-aquaculture.
39. AquaVitae. Case Study 1 - Production of new species of macroalgae 2019.
40. AquaVitae. Case Study 2 - Offshore macroalgae cultivation 2019.
41. AquaVitae. Case Study 6 - Sea urchin roe enhancement 2019.
42. AquaVitae. Case Study 8 - Improving seed availability and grow-out of native and non-native oysters 2019.
43. AquaVitae. Case Study 9 - Offshore production of blue mussels 2019.
44. Nagarajan D, Varjani S, Lee D-J, Chang J-S. Sustainable aquaculture and animal feed from microalgae – Nutritive value and techno-functional components. Renewable and Sustainable Energy Reviews 2021; 150:111549. Available from: URL: https://www.sciencedirect.com/science/article/pii/S1364032121008273.
45. Sanches-Fernandes GMM, Sá-Correia I, Costa R. Vibriosis Outbreaks in Aquaculture: Addressing Environmental and Public Health Concerns and Preventive Therapies Using Gilthead Seabream Farming as a Model System. Front Microbiol 2022; 13:904815.
46. Monzón-Atienza L, Bravo J, Serradell A, Montero D, Gómez-Mercader A, Acosta F. Current Status of Probiotics in European Sea Bass Aquaculture as One Important Mediterranean and Atlantic Commercial Species: A Review. Animals (Basel) 2023; 13(14).
47. AquaVitae. Case Study 5 - Biofloc and pond-based IMTA 2019.
48. Cerezuela R, Guardiola FA, Meseguer J, Esteban MÁ. Enrichment of gilthead seabream (Sparus aurata L.) diet with microalgae: effects on the immune system. Fish Physiol Biochem 2012; 38(6):1729–39.
49. AlgaEnergy. Aquaculture - AlgaEpiscis; 2024 [cited 2024 Jun 12]. Available from: URL: https://www.algaenergy.com/solutions/aquaculture/.
50. ASEBIO. Spanish Green Biotech Pipeline 2014 [cited 2024 Jun 12]. Available from: URL: https://dbtindia.gov.in/sites/default/files/GREENBIOTECHPIPELINE_2014.pdf.
51. Bosch-Belmar M, M'Rabet C, Dhaouadi R, Chalghaf M, Daly Yahia MN, Fuentes V et al. Jellyfish Stings Trigger Gill Disorders and Increased Mortality in Farmed Sparus aurata (Linnaeus, 1758) in the Mediterranean Sea. PLOS ONE 2016; 11(4):e0154239. Available from: URL: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0154239.
52. Kalaitzidou MP, Nannou CI, Lambropoulou DA, Papageorgiou KV, Theodoridis AM, Economou VK et al. First report of detection of microcystins in farmed mediterranean mussels Mytilus galloprovincialis in Thermaikos gulf in Greece. Journal of Biological Research-Thessaloniki 2021 [cited 2024 Jul 1]; 28:1–14. Available from: URL: https://link.springer.com/content/pdf/10.1186/s40709-021-00139-4.pdf.
53. AAC. Recommendation- Risks of bivalve mollusc pathogen emergence in connection with climate change 2022.
54. Guarini J-M, Hinz S, Coston-Guarini J. Designing the Next Generation of Condition Tracking and Early Warning Systems for Shellfish Aquaculture. JMSE 2021; 9(10):1084.
55. Overton K, Dempster T, Oppedal F, Kristiansen TS, Gismervik K, Stien LH. Salmon lice treatments and salmon mortality in Norwegian aquaculture: a review. Reviews in Aquaculture 2019; 11(4):1398–417.
56. Ferreira JG, Taylor NG, Cubillo A, Lencart-Silva J, Pastres R, Bergh Ø et al. An integrated model for aquaculture production, pathogen interaction, and environmental effects. 0044-8486 2021; 536:736438. Available from: URL: https://www.sciencedirect.com/science/article/pii/s0044848621001009.
57. Vereycken JE, Aldridge DC. Bivalve molluscs as biosensors of water quality: state of the art and future directions. Hydrobiologia 2023; 850(2):231–56.
58. S-3 Eurohab. S-3 EUROHAB : Sentinel products for detecting EUtROphication and Harmful Algal Bloom events; 2022 [cited 2024 Jul 2]. Available from: URL: https://www.s3eurohab.eu/.
59. Ifremer. REPHY : la surveillance du phytoplancton et des phycotoxines; 2023 [cited 2024 Jul 1]. Available from: URL: https://littoral.ifremer.fr/Reseaux-de-surveillance/Environnement/REPHY-la-surveillance-du-phytoplancton-et-des-phycotoxines.

60. AVRAMAR. Sustainability Report; 2022 [cited 2024 Jun 7]. Available from: URL: https://www.avramar.eu/wp-content/flipbook/Avramar_Sustainability_Report_2022_flipbook/Avramar-Sustainability_Report_2022.html.
61. Han P, Lu Q, Fan L, Zhou W. A Review on the Use of Microalgae for Sustainable Aquaculture. Applied Sciences 2019; 9(11):2377.
62. Dvarskas A, Bricker SB, Wikfors GH, Bohorquez JJ, Dixon MS, Rose JM. Quantification and Valuation of Nitrogen Removal Services Provided by Commercial Shellfish Aquaculture at the Subwatershed Scale. Environ Sci Technol 2020; 54(24):16156–65.
63. Macias, J.C., Avila Zaragozá, P., Karakassis, I. et al. Allocated zones for aquaculture - A guide for the establishment of coastal zones dedicated to aquaculture in the Mediterranean and the Black Sea.
64. d'Orbcastel ER, Lutier M, Le Floc'h E, Ruelle F, Triplet S, Le Gall P et al. Marine ecological aquaculture: a successful Mediterranean integrated multi-trophic aquaculture case study of a fish, oyster and algae assemblage. Aquaculture International; 30(6):3143–57.
65. AquaVitae. Case Study 3 - Land Based IMTA 2019.
66. AquaVitae. Case Study 4 - Sea-based Integrated Multi-trophic Aquaculture (IMTA) 2019.
67. Fernández-Rodríguez MJ, Milstein A, Jiménez-Rodríguez A, Mazuelos N, Medialdea M, Serrano L. Multivariate factor analysis reveals the key role of management in integrated multitrophic aquaculture of veta la Palma (Spain). 0044-8486 2018; 495:484–95. Available from: URL: https://www.sciencedirect.com/science/article/pii/S0044848616311504.
68. Hossain M, Hasan MR. An assessment of impacts from shrimp aquaculture in Bangladesh and prospects for improvement: FAO; 2017 [cited 2024 Jul 1]. Available from: URL: https://www.cabidigitallibrary.org/doi/full/10.5555/20193067208.
69. Kaminski AM, Pounds AM, McAdam B, Bostock J, Opiyo MA, Little DC. Growing smaller fish for inclusive markets? Increasing stocking density and shortening the production cycle of Nile tilapia in cages on Lake Victoria. Aquaculture 2024; 581:740319.
70. Fitzer SC, Torres Gabarda S, Daly L, Hughes B, Dove M, O'Connor W et al. Coastal acidification impacts on shell mineral structure of bivalve mollusks. Ecol Evol 2018; 8(17):8973–84.
71. DPI. Molluscan aquaculture; 2024 [cited 2024 Jun 7]. Available from: URL: https://www.dpi.nsw.gov.au/fishing/fisheries-research/aquaculture-research/molluscan-aquaculture.
72. SCCWRP. Dynamic exposure lab used to simulate pH buffering effects of kelp forests on oyster larvae. Southern California Coastal Water Research Project 2019 Nov 8 [cited 2024 Jun 7]. Available from: URL: https://www.sccwrp.org/news/dynamic-exposure-lab-used-to-simulate-ph-buffering-effects-of-kelp-forests-on-oyster-larvae/.
73. Cornejo-Ponce L, Vilca-Salinas P, Lienqueo-Aburto H, Arenas MJ, Pepe-Victoriano R, Carpio E et al. Integrated Aquaculture Recirculation System (IARS) Supported by Solar Energy as a Circular Economy Alternative for Resilient Communities in Arid/Semi-Arid Zones in Southern South America: A Case Study in the Camarones Town. Water 2020; 12(12):3469.
74. Soliman NF. Aquaculture in Egypt under Changing Climate: Challenges and Opportunities; 2017.
75. Agriloops. Des gambas françaises, ultra-fraîches et durables; 2024 [cited 2024 Jul 1]. Available from: URL: https://www.agriloops.com/homepage-agriloops.
76. LISAQUA. Low-Impact & Sustainable Aquaculture; 2024 [cited 2024 Jul 1]. Available from: URL: https://www.lisaqua.com/.
77. Plan Bleu. Blue Economy in the Mediterranean: Case studies, lessons and perspectives 2020 [cited 2024 Jul 1]. Available from: URL: https://planbleu.org/wp-content/uploads/2020/09/cahier19_Blue_Economy_EN.pdf.
78. AquaVitae. Case Study 11 - Marine Fish Farming [cited 2024 Jul 1]. Available from: URL: https://aquavitaeproject.eu/wp-content/uploads/2022/05/av_cs11_practice_abstract-Marine-Fish-Farming.pdf.
79. Bakiu R. Innovation towards the sustainability of Mediterranean blue economy: European Week Brussels; 2019.
80. UNITED. About the projects; 2024 [cited 2024 Jun 12]. Available from: URL: https://www.h2020united.eu/about.
81. Kaleem O, Bio Singou Sabi A-F. Overview of aquaculture systems in Egypt and Nigeria, prospects, potentials, and constraints. Aquaculture and Fisheries 2021; 6(6):535–47.
82. Hossain PR, Amjath-Babu TS, Krupnik TJ, Braun M, Mohammed EY, Phillips M. Developing Climate Information Services for Aquaculture in Bangladesh: A Decision Framework for Managing Temperature and Rainfall Variability-Induced Risks. Front. Sustain. Food Syst. 2021; 5.
83. Townhill BL, Tinker J, Jones M, Pitois S, Creach V, Simpson SD et al. Harmful algal blooms and climate change: exploring future distribution changes. ICES Journal of Marine Science 2018 [cited 2024 Jul 2]; 75(6):1882–93.
84. Liu W, Yu Z, Huang X, Shi Y, Lin J, Zhang H et al. Effect of ocean acidification on growth, calcification, and gene expression in the pearl oyster, Pinctada fucata. Marine Environmental Research 2017; 130:174–80. Available from: URL: https://www.sciencedirect.com/science/article/pii/S014111361730209X.
85. Boyd CE, D'Abramo LR, Glencross BD, Huyben DC, Juarez LM, Lockwood GS et al. Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. J World Aquaculture Soc 2020; 51(3):578–633. Available from: URL: https://onlinelibrary.wiley.com/doi/10.1111/jwas.12714.
86. FAO. Towards blue transformation. Rome: FAO; 2022. (The state of world fisheries and aquaculture; vol 2022) [cited 2024 Jun 26]. Available from: URL: https://openknowledge.fao.org/server/api/core/bitstreams/a2090042-8cda-4f35-9881-16f6302ce757/content.
87. El-Sayed A-FM. Alternative_dietary_protein_sources_for 1999.
88. Olmix. Olmix - Innovative biosourced solutions for a smart and sustainable agriculture; 2024 [cited 2024 Jun 26]. Available from: URL: https://olmix.com/.
89. AquaVitae. Case Study 13 - Low-trophic aquafeeds [cited 2024 Jun 27]. Available from: URL: https://aquavitaeproject.eu/wp-content/uploads/2022/05/av_cs13_practice_abstract_vfinal.pdf.
90. AquaVitae. Case Study 12 - Use of by-products [cited 2024 Jun 27]. Available from: URL: https://aquavitaeproject.eu/wp-content/uploads/2022/05/av_cs12_practice_abstract.pdf.

91. Yep B, Zheng Y. Aquaponic trends and challenges – A review. Journal of Cleaner Production 2019; 228:1586–99. Available from: URL: https://www.sciencedirect.com/science/article/pii/s0959652619313812.

92. Vasdravanidis C, Alvanou MV, Lattos A, Papadopoulos DK, Chatzigeorgiou I, Ravani M et al. Aquaponics as a Promising Strategy to Mitigate Impacts of Climate Change on Rainbow Trout Culture. Animals (Basel) 2022; 12(19).

93. MacLeod MJ, Hasan MR, Robb DHF, Mamun-Ur-Rashid M. Quantifying greenhouse gas emissions from global aquaculture. Sci Rep 2020 [cited 2024 Jul 2]; 10(1):11679. Available from: URL: https://www.nature.com/articles/s41598-020-68231-8.pdf.

94. Alleway HK, Jones AR, Theuerkauf SJ, Jones RC. A global and regional view of the opportunity for climate-smart mariculture. Philos Trans R Soc Lond B Biol Sci 2022 [cited 2024 Jun 27]; 377(1854):20210128. Available from: URL: https://royalsocietypublishing.org/doi/pdf/10.1098/rstb.2021.0128.

95. Alleway HK. Climate benefits of seaweed farming. Nat Sustain 2023; 6(4):356–7. Available from: URL: https://www.nature.com/articles/s41893-022-01044-x.

96. European Commission. Impact Assessment Report on the Regulation for a Union Certification Framework for Carbon Removals. Brussels; 2022.

97. Maar M, Holbach A, Boderskov T, Thomsen M, Buck BH, Kotta J et al. Multi-use of offshore wind farms with low-trophic aquaculture can help achieve global sustainability goals. Commun Earth Environ 2023; 4(1):1–14. Available from: URL: https://www.nature.com/articles/s43247-023-01116-6.

98. Thomas Y, Cassou C, Gernez P, Pouvreau S. Oysters as sentinels of climate variability and climate change in coastal ecosystems. Environ. Res. Lett. 2018; 13(10):104009. Available from: URL: https://iopscience.iop.org/article/10.1088/1748-9326/aae254/meta.

99. Le Gouvello R, Hochart L-E, Laffoley D, Simard F, Andrade C, Angel D et al. Aquaculture and marine protected areas: Potential opportunities and synergies. Aquatic Conservation 2017; 27(S1):138–50.

100. Brugère C, Aguilar-Manjarrez J, Beveridge MCM, Soto D. The ecosystem approach to aquaculture 10 years on – a critical review and consideration of its future role in blue growth. Reviews in Aquaculture 2019; 11(3):493–514.

101. FAO. Aquaculture development. 4. Ecosystem approach to aquaculture; 2010 [cited 2024 Jun 17]. Available from: URL: https://www.fao.org/4/i1750e/i1750e00.htm.

102. Matulić D, Andabaka Ž, Radman S, Fruk G, Leto J, Rošin J et al. Agrivoltaics and Aquavoltaics: Potential of Solar Energy Use in Agriculture and Freshwater Aquaculture in Croatia. Agriculture 2023; 13(7):1447.

103. GEPS Technology. Our Innovation Lab approach: from need to service; 2024 [cited 2024 Jun 27]. Available from: URL: https://geps-techno.com/en/our-approach-innovation-lab/.

104. OLAMUR. OLAMUR : Offshore Low-Trophic Aquaculture in Multi-use Scenario Realisation in North and Baltic Seas; 2024 [cited 2024 Jun 27]. Available from: URL: https://olamur.eu/?r34icsym=202407.

105. Menicou M, Vassiliou V. Prospective energy needs in Mediterranean offshore aquaculture: Renewable and sustainable energy solutions. Renewable and Sustainable Energy Reviews 2010; 14(9):3084–91.

106. Vo TTE, Ko H, Huh J-H, Park N. Overview of Solar Energy for Aquaculture: The Potential and Future Trends. Energies 2021; 14(21):6923. Available from: URL: https://www.mdpi.com/1996-1073/14/21/6923.

107. Giangrande A, Pierri C, Arduini D, Borghese J, Licciano M, Trani R et al. An Innovative IMTA System: Polychaetes, Sponges and Macroalgae Co-Cultured in a Southern Italian In-Shore Mariculture Plant (Ionian Sea). JMSE 2020; 8(10):733.

108. Walton M, Vilas C, Cañavate JP, Gonzalez-Ortegon E, Prieto A, van Bergeijk SA et al. A model for the future: Ecosystem services provided by the aquaculture activities of Veta la Palma, Southern Spain. 0044-8486 2015; 448:382–90. Available from: URL: https://www.sciencedirect.com/science/article/pii/S0044848615300582.

109. AAC. Recommendations for Climate Change Adaptation and Mitigation in Aquaculture 2023.

110. Zoli M, Rossi L, Bibbiani C, Bacenetti J. Life cycle assessment of seabass and seabream production in the Mediterranean area: A critical review. 0044-8486 2023; 573:739580. Available from: URL: https://www.sciencedirect.com/science/article/pii/s004484862300354x.

111. Bartley DM, Brugère CD, Soto D, Gerber P, Harvey BJ. Comparative assessment of the environmental costs of aquaculture and other food production sectors: Methods for meaningful comparisons FAO WFT Expert Workshop, 24-28 April 2006, Vancouver, Canada. Rome: Food and Agriculture Organization of the United Nations; 2007. (FAO fisheries proceedings; vol 10).

112. AAC. Recommendations on the Decarbonisation of Energy Aquaculture Vessels 2023.

113. Viart C. Lancement d'une barge électrique pour les ostréiculteurs bretons. Le marin 2022 Jul 11 [cited 2024 Jun 17]. Available from: URL: https://lemarin.ouest-france.fr/peche/lancement-dune-barge-electrique-pour-les-ostreiculteurs-bretons-419e9982-7c8a-4bdb-afdd-43de10659816.

114. Hou E-J, Huang C-S, Lee Y-C, Chu H-T. Upcycled aquaculture waste as textile ingredient for promoting circular economy. Sustainable Materials and Technologies 2022; 31:e00336. Available from: URL: https://www.sciencedirect.com/science/article/pii/S2214993721000919.

115. FAO. STATE OF WORLD FISHERIES AND AQUACULTURE 2024: Blue transformation in action. [S.l.]: Food & Agriculture Org; 2024 [cited 2024 Jun 25]. Available from: URL: https://openknowledge.fao.org/server/api/core/bitstreams/a4151f1e-3130-4504-a7d7-4b066de59030/content.

116. Beyer CP, Gómez S, Lara G, Monsalve JP, Orellana J, Hurtado CF. Sarcocornia neei: A novel halophyte species for bioremediation of marine aquaculture wastewater and production diversification in integrated systems. Aquaculture 2021; 543:736971.

117. Ahmed N, Turchini GM. Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. Journal of Cleaner Production 2021; 297:126604. Available from: URL: https://www.sciencedirect.com/science/article/pii/S0959652621008246.

118. Bregnballe J. A guide to Recirculation aquaculture: an introductin to the new environmentally friendly and highly productive closed fish farming systems. FAO.

119. Murray F, Bostock J, Fletcher D. Review of Recirculation Aquaculture System: Technologies and their Commercial Application 2014.

120. Giangrande A, Gravina MF, Rossi S, Longo C, Pierri C. Aquaculture and Restoration: Perspectives from Mediterranean Sea Experiences. Water 2021; 13(7):991.

121. NOAA. Offshore Aquaculture Permitting Guide; 2024 [cited 2024 Jun 17]. Available from: URL: https://www.fisheries.noaa.gov/pacific-islands/aquaculture/offshore-aquaculture-permitting-guide.

122. Yücel Gier G. Aquaculture zoning, site selection and area management under the ecosystem approach to aquaculture.: Mariculture Parks in Turkey. Washington, DC; 2017. Available from: URL: https://scholar.google.de/citations?user=odsvx3aaaaaj&hl=de&oi=sra.

123. Gentry RR, Lester SE, Kappel CV, White C, Bell TW, Stevens J et al. Offshore aquaculture: Spatial planning principles for sustainable development. Ecol Evol 2017; 7(2):733–43.

124. Soukissian T, Denaxa D, Karathanasi F, Prospathopoulos A, Sarantakos K, Iona A et al. Marine Renewable Energy in the Mediterranean Sea: Status and Perspectives. Energies 2017; 10(10):1512.

125. UNDP. Climate Smart Aquaculture: A Toolkit for Policymakers and Investors 2022.

126. Pham TTT, Friðriksdóttir R, Weber CT, Viðarsson JR, Papandroulakis N, Baudron AR et al. Guidelines for co-creating climate adaptation plans for fisheries and aquaculture. Climatic Change 2021; 164(3-4):1–20. Available from: URL: https://link.springer.com/article/10.1007/s10584-021-03041-z.

127. Cao Le Quyen, Trinh Quang Tu, Phan Phuong Thanh, Nguyen Duc Trung, Ta Thanh Nghi, Liew P. Factors affecting the adoption of climate-smart aquaculture (CSAq) in the North Central Coast of Vietnam; 2019. Available from: URL: https://cgspace.cgiar.org/handle/10568/101297.

128. WorldFish. A Training Dialogue Report: Introduction to climate services for aquaculture. Capacitating farmers and fishers to manage climate risks in South Asia (CaFFSA) 2020.

129. FAO. Toolkit on allocated zones for aquaculture 2019.

130. AlgaEnergy. AlgaEnergy shows the contribution of microalgae in facing the climate change at COP25; 2019 [cited 2024 Jun 18]. Available from: URL: https://www.algaenergy.com/news/algaenergy-shows-the-contribution-of-microalgae-in-facing-the-climate-change-at-cop25/.

131. Banerjee I, Dutta S, Pohrmen CB, Verma R, Singh D. Microalgae-based carbon sequestration to mitigate climate change and application of nanomaterials in algal biorefinery. Octa J Biosci 2020; 8:129–36. Available from: URL: https://www.researchgate.net/profile/ishita-banerjee-5/publication/348279383_microalgae-based_carbon_sequestration_to_mitigate_climate_change_and_application_of_nanomaterials_in_algal_biorefinery/links/5ff5f24fa6fdccdcb8359c3e/microalgae-based-carbon-sequestration-to-mitigate-climate-change-and-application-of-nanomaterials-in-algal-biorefinery.pdf.

132. Weiss CVC, Menendez M, Ondiviela B, Guanche R, Losada IJ, Juanes J. Climate change effects on marine renewable energy resources and environmental conditions for offshore aquaculture in Europe. ICES J Mar Sci 2020; 77(7-8):3168–82.

133. Aquafeed UK. Animal Protein in Bangladesh and Maledives Comes From Seafood: Creative Commons License.; 2023 [cited 2024 Jul 12].

134. AquaVitae. Sustainable Aquaculture Low Trophic Species.; 2022 [cited 2024 Jul 12].

135. Pxhere. Seafood, mussels.: Creative Commons License.; 2024 [cited 2024 Jul 12]. Available from: URL: https://pxhere.com/en/photo/493227.

136. Pxhere. Seafood, shrimp.: Creative Commons License.; 2024 [cited 2024 Jul 12]. Available from: URL: https://pxhere.com/en/photo/571850.

137. Yücel-Gier G. Mariculture Parks in Turkey. In: Aguilar-Manjarrez J, Soto D, Brummett R, editors. Aquaculture zoning, site selection and area management under the ecosystem approach to aquaculture - Full document. Rome; 2017.

138. Kara, M. H., Lacroix, D., Rey-Valette, H., Mathé, S., Blancheton, J. P. 2018: Dynamics of Research in Aquaculture in North Africa and Support for Sustainable Development and Innovation. Reviews in Fisheries Science & Aquaculture 26, 309–318. doi :10.1080/23308249.2017.1410521

139. Moatti J.P. et S. Thiébaud, 2018 : the Mediterranean region under climate change. IRD Editions. 736 p. doi: 10.400/books. IRD éditions.22908

140. Euzen A., F. Gaill, D. Lacroix et P. Cury (dir.), 2019 : L'Océan à Découvert ; CNRS Éditions, (coord. 152 contributions)

VIII. Glossary

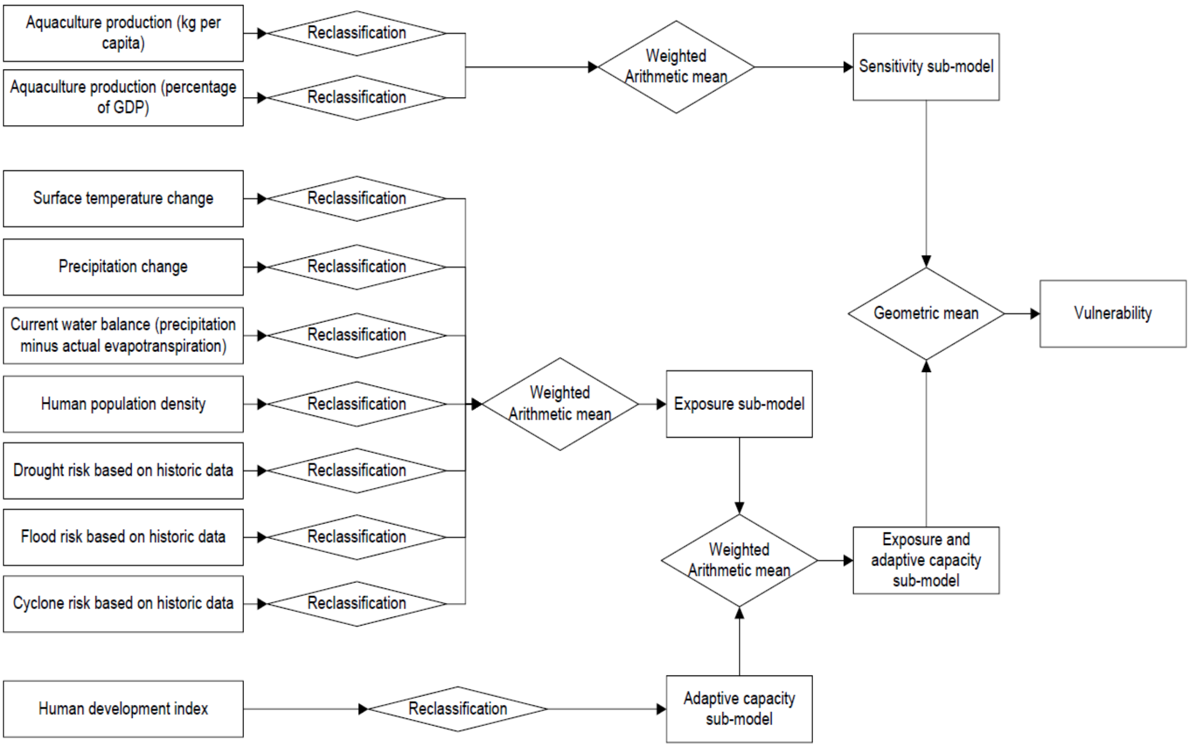
ADC	**Aquaculture Demonstrative Centres.** The General Fisheries Commission for the Mediterranean (GFCM) of the Food and Agriculture Organization of the United Nations (FAO) has launched three Aquaculture Demonstrative Centres (ADCs) showcasing best practices, educational programs, and hands-on technical support.
AZA	**Allocated Zones for Aquaculture.** AZA are suitable marine areas for aquaculture, where aquaculture is prioritized over other marine activities, and where interferences are minimized or avoided (129) .
BEWS	**Biological Early Warning Systems.** Biological early warning systems (BEWSs) monitor the behaviour or physiology of living organisms as an indirect mechanism to sense local environmental changes, and have become a widely established tool for monitoring water pollution (57).
CAP	**Climate Adaptation Plan.** A promising regulatory enabler could be the inclusion of Climate Adaptation Plans (CAP) or Climate Smart Aquaculture (CSA)[1] in the National Adaptation Program of Actions (NAPA) (2, 125). CSA applied in aquaculture include IMTA, selection of CC-tolerant genetic strains and species, or increased RAS to reduce the need for freshwater (2). This could result in an overarching strategy within a country to address CC and its impacts on the aquaculture sector (2). This approach termed CAP by the EU (18, 126) , stresses stakeholder participation, and combines bottom-up and top-down approaches (33).
CC	**Climate Change**. Climate change refers to long-term shifts in temperatures and weather patterns.
CSA/ CSAq	**Climate-Smart Aquaculture.** CSA is defined as “aquaculture that sustainably increases productivity, resilience (adaptation), reduces/removes greenhouse gases (mitigation), and enhances the achievement of national food security and development goals” (125).
EAA	**Ecosystem Approach for Aquaculture.** The EAA describes a method of how these projects should be implemented. Elements like stakeholder integration for sustainable development, equity, and resilience of interlinked social-ecological systems are essential for the success of the EAA project (101).
EWS	**Early Warning Services.** An integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events.
HAB	**Harmful Algae Blooms**. HABs occur when colonies of algae grow out of control and produce toxic or harmful effects on people, fish, shellfish, marine mammals and birds.
ICZM	**Integrated Coastal Zone Management**. ICZM is a dynamic, multidisciplinary and iterative process to promote sustainable management of coastal zones.
IMTA	**Integrated Multi-Trophic Aquaculture.** IMTA involves simulating a co-culture system that mimics a natural aquatic ecosystem, entailing multiple tropic levels arranged in a way to harness the potential of by-products and thereby minimize waste production.
MSP	**Maritime Spatial Planning**. MSP is a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that have been specified through a political process.

NAPA	**National Adaptation Program of Actions.** NAPAs provide a process for the least developed countries to identify priority activities that respond to their urgent and immediate needs with regard to adaptation to climate change - those needs for which further delay could increase vulnerability or lead to increased costs at a later stage.
ORE	**Offshore Renewable Energy**. ORE, comprising marine (wave and tidal energy), and offshore wind, has the potential to supply large amounts of 'green' sustainable energy, reducing CO_2 emissions.
RAS	**Recirculating Aquaculture Systems.** RAS are land-based aquaculture facilities – either open air or indoors – that minimise water consumption by filtering, adjusting, and reusing the water.
RE	**Renewable Energy.** RE is energy derived from natural sources that are replenished at a higher rate than they are consumed. Sunlight and wind, for example, are such sources that are constantly being replenished.
SDGs	**Sustainable Development Goals.** The SDGs are 17 global targets to achieve a better and more sustainable future for all by 2030. They address poverty, inequality, climate change, environmental degradation, peace and justice.
SMEs	**Small and Medium-size Enterprises.** SMEs have fewer than 250 persons employed and a turnover equal or below to 50 million € or a balance sheet total equal to or below 43 million €.
UNDP	**United Nations Development Programme.** UNDP is the United Nations' lead agency on international development and supports countries and communities to eradicate poverty, implement the Paris Agreement on climate change and achieve the Sustainable Development Goals.
UNEP/MAP	**United Nations Environment Programme's Mediterranean Action Plan.** The Mediterranean Action Plan (MAP) of the United Nations Environment Programme was established in 1975 by Mediterranean governments as the first regional action plan under the UNEP Regional Seas Programme with clear objectives to foster regional collaboration for combatting marine pollution and promoting integrated planning and sustainable use of marine resources. At the heart of MAP lies the Convention for the Protection of the Mediterranean Sea Against Pollution (Barcelona Convention), which was signed on 16 February 1976 in Barcelona, Spain, and entered into force on 12 February 1978.
NMCs	**Northern Mediterranean Countries.** The classification used in this report includes the following countries for the NMCs: EU countries (Cyprus, France, Greece, Italy, Malta, Portugal, Slovenia, Spain) and non EU countries (Albania, Bosnia Herzegovina, Croatia, FYROM, Serbia).
SEMCs	**South Eastern Mediterranean Countries.** The classification used in this report includes the following countries for the SEMCs: Algeria, Egypt, Libya, Morocco, Tunisia, Turkey, Israel, Jordan, Lebanon, Palestine, Syria.

IX. Appendix

A. Annex 1: Vulnerability Assessment

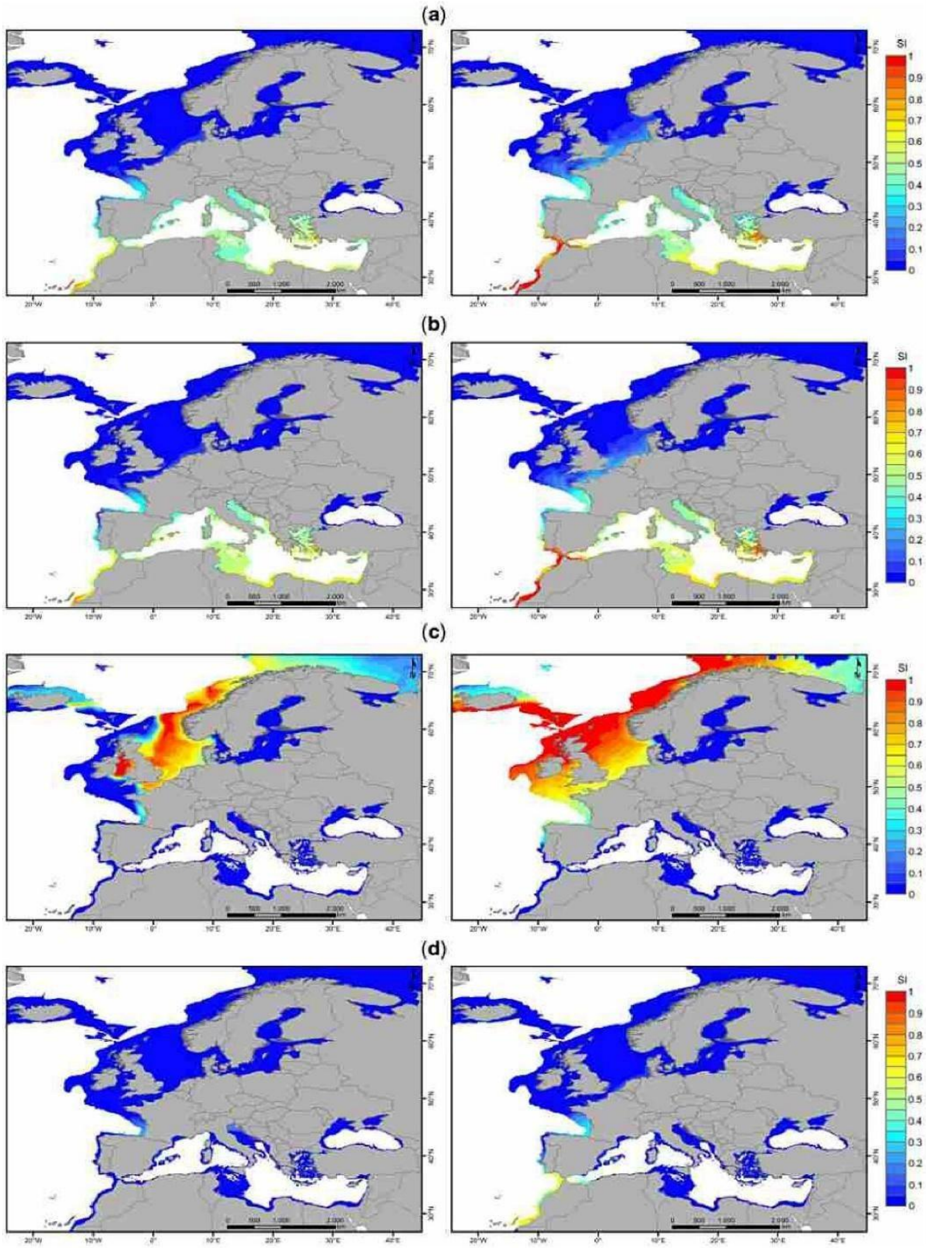
The co-authors of (1) were contacted but were unable to provide the exact vulnerability values for the Mediterranean country, as the lead author could not be reached. Therefore, an alternative approach was adopted. The colors from the original map for global vulnerability were ranked and synthesized in a table. This was done to receive a classification for the vulnerability of the countries within the Mediterranean basin.



B. Annex 2: Offshore aquaculture - High-value or low trophic species?

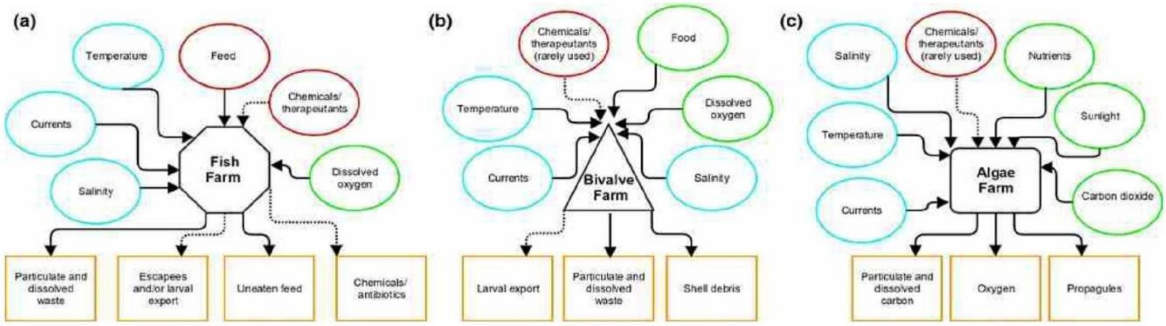
There are different aspects to consider when planning offshore aquaculture facilities for high-value or low-trophic species. **High-value species.** In Figure 11 the offshore suitability regarding the climate change impacts, temperature, and salinity, for different species is assessed. The maps for (a) represent the suitability for Meagre, Gilthead seabream, and Atlantic Bluefin tuna and (b) for European seabass concerning these two CC impacts. On the left side, a time frame from 1979-2015 is shown, and on the right side from 2070-2099. For the Mediterranean basin, one could argue that CC suitability for these high-value species increases with accelerating climate change. Nevertheless, several factors have not been taken into account in this modeling, such as the increasing risk for pathogens or extreme weather events.

Figure 11. Suitability assessment based on the climate change impacts (temperature and salinity) for (a) Meagre, Gilthead sea-bream, Atlantic bluefin tuna (b) European seabass. The left column shows the timeframe [1979-2015] and the right column [2070-2099]. Suitability index (SI) varies between 0 = minimum suitability to 1= maximum suitability) (132).



To further assess the practical suitability of different aquaculture types for the offshore areas, inputs, and outputs could be assessed. These are displayed in Figure 12. According to different local contexts, inputs and outputs could pose a problem or could help to mitigate climate change effects. This underlines again, the need for further regional vulnerability assessments that take into account more factors than salinity and temperature to give recommendations for suitable aquaculture offshore sites for specific species (132).

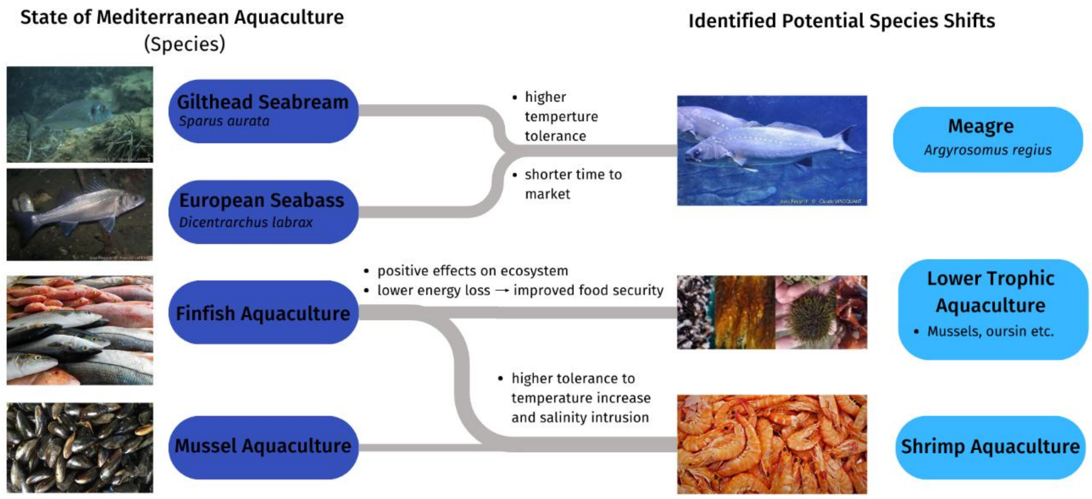
Figure 12. Schematic of key inputs and outputs associated with the three major categories of aquaculture: (a) fed, (b) unfed, and (c) autotrophic. Red indicates external inputs into the farm, green indicates environmental inputs; blue indicates other environmental conditions that affect the farm; and orange indicates outputs from the farm into the environment. (123)



C. Annex 3: Species shifts for CC adaptation of Mediterranean aquaculture

In Figure 13 proposed species shifts for CC adaptation of Mediterranean aquaculture are visualized. These propositions were discussed in Chapter III.A, Chapter III.C, and Table *2*.

Figure 13. Shifting species for climate change adaptation of Mediterranean aquaculture



Species - source: DORIS FFESSM
https://doris.ffessm.fr/Especes/Sparus-aurata-Dorade-daurade-royale-465
https://aquavitaeproject.eu/wp-content/uploads/2022/07/mooc_sustainable_aquaculture_low-trophic-species-850x425.png

creative commons licence:
https://www.aquafeed.co.uk/wp-content/uploads/2023/12/60-Of-the-Animal-Protein-in-Bangladesh-and-Maldives-Comes-From-Seafood.jpg (creative commons)
https://pxhere.com/en/photo/493227 (mediterranean mussel?)
https://pxhere.com/en/photo/571850