Chapter 18
Ocean Acidification as a Governance Challenge in the Mediterranean Sea: Impacts from Aquaculture and Fisheries

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Abstract Despite the progress in the international and regional governance efforts at the level of climate change, ocean acidification (OA) remains a global problem with profoundly negative environmental, social, and economical consequences. This requires extensive mitigation and adaptation effective strategies that are hindered by current shortcomings of governance. This multidisciplinary chapter investigates the risks of ocean acidification (OA) for aquaculture and fisheries in the Mediterranean Sea and its sub-basins and the role of regional adaptive governance to tackle the problem. The identified risks are based on the biological sensitivities of the most important aquaculture species and biogenic habitats and their exposure to the current and future predicted (2100) RCP 8.5 conditions. To link OA exposure and biological sensitivity, we produced spatially resolved and depth-related pH and

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aragonite saturation state exposure maps and overlaid these with the existing aquaculture industry in the coastal waters of the Mediterranean basin to demonstrate potential risk for the aquaculture in the future. We also identified fisheries' vulnerability through the indirect effects of OA on highly sensitive biogenic habitats that serve as nursery and spawning areas, showing that some of the biogenic habitats are already affected locally under existing OA conditions and will be more severely impacted across the entire Mediterranean basin under 2100 scenarios. This provided a regional vulnerability assessment of OA hotspots, risks and gaps that created the baseline for discussing the importance of adaptive governance and recommendations for future OA mitigation/adaptation strategies. By understanding the risks under future OA scenarios and reinforcing the adaptability of the governance system at the science-policy interface, best informed, "situated" management response capability can be optimised to sustain ecosystem services.

18.1 Introduction

In the era defined as the Anthropocene (Crutzen 2002), global oceans have already been profoundly altered by humans. Increasing levels of human made greenhouse gas emissions of which 25% has been absorbed by the oceans (Sabine et al. 2004; Le Quéré et al. 2018; Bindoff et al. 2019; Licker et al. 2019). This has led to an increase of surface seawater acidity of approximately 30% (Doney et al. 2009). This process, referred to as "Ocean Acidification" (OA), is a complex global phenomenon that is among the nine planetary boundaries identified by Rockström et al. (2009). Although global, OA has "situated" effects on regional and marginal seas such as the Mediterranean Sea and its sub-basins. These effects impact the regional ecosystems, biodiversity, and ecosystem services, including aquaculture, fisheries and food security (Barbier 2017; Bindoff et al. (2019), with significant implications

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on the overall Mediterranean socio-ecological system (Hassoun et al. 2022; Zunino et al. 2021). OA introduces additional complexity in governance efforts because the source of the problem occurs at a different time and space scales than the locus of the affected people (Long 2009) and ecosystems.

Thousands of years of history have shaped the governance of the semi-enclosed Mediterranean Sea. From tensions and conflicts between coastal populations over access to the sea, its resources, or adjacent lands, to enhanced cooperation because of a shared cultural and natural heritage. In terms of marine biodiversity, the Mediterranean is considered a hotspot of marine biodiversity as it hosts high percentages of endemic species (Coll et al. 2012). However, areas of high diversity overlap with areas where there is high potential for cumulative threats such as unsustainable development and climate change linked events (including temperature rise, marine heat waves, OA, deoxygenation, eutrophication, freshening, overfishing, chemical pollution, and habitat destruction) (Giorgi, 2006; Shaltout and Omstedt, 2014; Lazzari et al. 2014; Hilmi et al. 2015; Goyet et al. 2016; Cramer et al. 2018; Tuel and Eltahir 2020). Multiple climatic drivers are many and well documented. They are dynamic and interactive, resulting in negative cumulative impacts on the pelagic and benthic habitats that support the structural and functional biodiversity and productivity, as well as ecosystem services, like aquaculture and fisheries (Zunino et al. 2021). OA is therefore an additional challenge for the sustainability of Mediterranean socio-ecological systems and their governance. While OA as a stressor, temporally and spatially interacts with many drivers, there are spatial and temporal windows where OA is a main driver of the biological responses. Late fall or winter for example is characterized by low pH conditions, something which coincides with the shellfish spawning period. This requires a more in depth understanding of the OA exposure even as a single stressor.

Due to higher temperature and low local buffering capacity, the Mediterranean Sea is particularly sensitive to CO_2 increases in the atmosphere as they are quickly absorbed in the surface waters and rapidly transported to deeper water by overturning circulation (Cossarini et al. 2015, Melaku Canu et al. 2015; Simoncelli et al. 2018; Pinardi et al. 2019; Jiang et al. 2019; Cai et al. 2011, 2017; Hassoun et al. 2019; Wimart-Rousseau et al. 2021) as this results in lower pH and carbonate saturation states (Álvarez et al. 2014; Hassoun et al. 2015). Despite substantial spatial and temporal OA variability, fingerprinting of OA conditions show that the anthropogenic signal is already detectable across the Mediterranean Sea; in its Western basin for example with a decrease of 0.0028 pH unit/year (Luchetta et al. 2010; Kapsenberg et al. 2017; Ingrosso et al. 2017) and the Eastern Basin with a decline of 0.0021 pH unit/year (Hassoun et al. 2019). Surface pH is projected to decrease by about 0.24 and 0.46 pH units according to the 2100 IPCC SRES scenarios (Goyet et al. 2016), which is consistent with the global average (Geri et al. 2014; Goyet et al. 2016; Kapsenberg et al. 2017), but some parts of the Mediterranean might be exceeding the projected global change (Hassoun et al. 2015). The aim of this chapter is to provide a regional vulnerability assessment of OA hotspots, risks and gaps as a knowledge basis for the development of adaptive management options to combat OA and sustain ecosystem services in the Mediterranean Sea.

18.1.1 The Risks for Ecosystem Services in the Mediterranean Sea

OA impacts affect the integrity and functionality of ecosystems with cascading effect on the provisioning of ecosystem services, such as aquaculture and fisheries, and consequences to local economies (Barange et al. 2014; Gattuso et al. 2015). Such impacts are related to either direct, species-related negative effects on foundation or economically important species (Gaylord et al. 2015), or to the indirect effects related to the alteration of biogenic habitats, loss of biodiversity, changes in the availability of habitats, and general trophic web alterations (Sunday et al. 2016, Zunino et al. 2019, Zunino et al. 2021). Aquaculture and fisheries contribute to the recreational, provisioning and cultural services of marine ecosystems (Millennium Ecosystem Assessment 2005) and with fish aquaculture production projected to increase by 112% over the Mediterranean basin (Piante and Ody, 2015). The shellfish aquaculture is dominated by the production of the Mediterranean mussel (*Mytilus galloprovincialis*), followed by the Japanese carpet shell (*Ruditapes philippinarum*), whilst there is a limited production of other species (Massa et al. 2017). Fishery landings in the Mediterranean are dominated by small pelagics (herrings, sardines, anchovies; FAO 2018), with the Western Mediterranean subregion having the highest fisheries' capture, and closely followed by the Adriatic and the Central and Eastern Mediterranean sub-basins (FAO 2018).

Mediterranean mariculture is economically relevant to the sea-bordering states as 75% of this industry relies on the health of marine habitats in which climate change and OA are determinants of their productive efficiency (Rodrigues et al. 2015; Gazeau et al. 2014). Although wide variations exist in the sensitivities of different shellfish species of bivalves to OA (Range et al. 2014), they in general show negative impacts in growth and development, reduced calcification, and immunological and physiological alterations (Lemasson et al. 2017; Franke and Clemmesen 2011).The Mediterranean mussel (*M. galloprovincialis*) is the most extensively studied species with demonstrated sensitivity to OA, with the early warning response to reduced shell integrity being compromised at pH value of 7.7 (Michaelidis et al. 2005; Range et al. 2012; Bressan et al. 2014). The assessment of OA impacts on Mediterranean fisheries is complex because of species-specific sensitivities (Hilmi et al. 2014). In general, fishes seem to be physiologically more resilient to OA than bivalves (Michaelidis et al. 2007; Réveillac et al. 2015).

Major OA effects on fisheries might be related to the indirect impact on the variety of biogenic habitats that provide a unique environment and physical structure, and constitute hotspots for fisheries and species richness. Examples include seagrass beds (*Posidonia oceanica*), shellfish beds, variety of corals, crustose coralline algae, bryozoans, and vermetid reefs, all of which represent ecosystem engineers that provide a nursery habitat for fish and modify the substrata, contributing to numerous ecosystem functions and services (Fletcher and Breitling 2012; Milazzo et al. 2014). Biogenic habitats in the Mediterranean are already listed as endangered or vulnerable (Beal et al. 2016) with decreasing pH causing increased corrosion, skeletal loss and reduced calcareous algal cover (Martin and Gattuso 2009; Martin et al. 2008; Lombardi et al. 2011, Milazzo et al. 2014). Biogenic habitat of the red coral showed a significant decrease in skeletal calcification and polyp activity at reduced pH (Cerrano et al. 2013; Bramanti et al. 2013). Biogenic reefs have been historically subjected to a dramatic decline and are predicted to further decline due to climate change, diseases, and non-native species interaction (Rosa et al. 2012; Ingrosso et al. 2018; Badreddine et al. 2019a, b; Milazzo et al. 2019; Ragazzola et al. 2021).

18.1.2 OA Side-by-Side Governance

OA is an emerging governance challenge with a complex, uncertain, ever widening and transboundary nature. This nature as well as the potential ecological, economic as well as societal repercussions call for a need for tailored-specific OA solutions and mitigation strategies (Galdies et al. 2020; Tiller et al. 2019). It was only during the first Monaco Declaration on OA (Monaco, October 2008), when OA has been discussed in the political arena as a "parallel and interactive phenomenon" (Osborn et al. 2017). It has also been included as a separate target in SDG 14 (Life below Water) with Target 3 calling on States to minimize and address the impacts of OA. Nevertheless, there has been limited success in addressing OA leading scholars describing it as a "governance failure" (Jagers et al. 2019), or a "governance gap" (IPCC 2019). This is either due to the absence of relevant institutions or mechanisms of coordination, or inadequate mandates of existing organisations and mechanisms. This is also visible at the Mediterranean level where existing institutions, despite a certain robustness, adaptability, and governability, have not addressed the issue of OA in a concrete, specific, and binding manner.

At the supranational level, three overlapping and interacting governance frameworks are of potential relevance for regulating OA on the Mediterranean scale.[1] The first and more advanced framework is that of the European Union (EU).[2] However, EU-wide actions remain "incomprehensible and uncoordinated" (Galdies et al. 2020). Depending on political choices, economic activities or environmental components, the fight against OA may fall under various policies, including the marine and coastal policy, the nature and biodiversity policy, the water policy, the common fisheries and aquaculture policies or the climate policies. European decision-makers

[1] The governance of the OA problem also relies on the twenty-one riparian States, through their own domestic laws, institutions and policy processes, as well as their participation in regional or sectoral agreements and organisations such as the European Union. For an in-depth study of OA governance management at EU member States' level, see Galdies et al. 2020.

[2] The EU has exclusive competence in the conservation of marine biological resources under the Common Fisheries Policy (CFP) (Art. 3 TFEU), while its competence is shared with the Member States for fisheries (except conservation of marine biological resources), environment or research (Art. 4 TFEU).

have not yet discussed or even understood how these policies, under the responsibility of different Directorates General of the European Commission, could minimize and address the impacts of OA in an integrated, or at least effective manner. No minimum standards have been specified so far, such as binding targets (pH) for achieving good environmental status under the Marine Strategy Framework Directive.

The second relevant governance framework is the 1975/1995 Barcelona Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (in force 1976/2004) and its six Protocols administered by the UNEP (and to which the 21 riparian States are all contracting parties). Similar to the Convention on Biological Diversity and other regional or sectoral agreements such as OSPAR, the Barcelona Convention direct mitigation mandate is limited (*sensu* Herr et al. 2014) and relates to climate change rather than OA. Most of the information on OA circulated among its bureaucracy is scientific data.

The third relevant governance framework for OA at the Mediterranean scale is the management and conservation of fisheries under the mandate of the General Fisheries Commission for the Mediterranean (GFCM-FAO) and the International Commission for the Conservation of Atlantic Tunas (ICCAT). None of these Regional Fishery Management Organisations (RFMOs) have included OA in their scientific strategies (Herr et al. 2014). Such organisations remain guided by political-economic concerns and conservative in their approach to emerging scientific issues. Moreover, no reference to OA is made in the most recent reports of their fishery science bodies, the GFCM-FAO Scientific Advisory Committee on Fisheries (SAC) and the ICCAT Standing Committee on Research and Statistics (SCRS). Only the Scientific Advisory Committee on Aquaculture (CAQ) advised the GFMC-FAO members in its last report of 2017 to "incorporate aquaculture, climate change and ocean acidification issues in the system of indicators to monitor the sustainable development of aquaculture".[3]

In the light of its actors, structure, and processes, a "side-by-side governance" model is sustained in the issue area of OA on the Mediterranean scale (as on a global level), where the loci of action are so widely dispersed, unrelated, and situation-specific that neither the relevant governmental officials nor their transnational non-governmental counterparts can usefully resort to mass mobilisation. Instead, they must rely on interactive and multiple flows of influence (Rosenau 2000).[4] A side-by-side governance model is not necessarily an obstacle to solving the OA problem but could instead serve as a basis for adaptive governance. For that, Galdies et al. (2020) recommends a continued assessment in understanding the nature of the risks posed by OA in local and regional waters. The OA-related vulnerability risk assessment, which combines chemical exposure with the biological sensitivity (*sensu* Bednaršek

[3] General Fisheries Commission for the Mediterranean, Report of the tenth session of the Scientific Advisory Committee on Aquaculture, Izmir, Turkey, 27–29 March 2017, Doc. FIAP/R1206(Bi), p. 8.

[4] Public awareness remains low (Buckley et al. 2017; IPCC 2019; Tiller et al. 2019), OA being still often confused in its discernible reality with climate change.

et al. 2021), helps identify OA spatial-temporal hotspots, acknowledges the gaps and suggests appropriate adaptation strategies to provide desired results that can ultimately favour economic and social factors.

With this aim, the chapter presents a comprehensive OA vulnerability risk assessment related to the ecosystem services over the broad Mediterranean Sea basin. By linking regional OA exposure with the relevant biotic thresholds, we produced OA exposure maps to delineate the spatial-vertical-temporal OA hotspots for the aquaculture and the fisheries under current and future (2100) predicted conditions (Sect. 3). We used this vulnerability assessment to discuss the adaptive governance and institutional framework and focused on providing recommendations needed to deal efficiently with OA risks and policy-management responses for the sustainability of ecosystem services (Sect. 4) (*sensu* Ziveri et al. 2017: Osborn et al. 2017; Jagers et al. 2019; Galdies et al. 2020; Galdies et al. 2021).

18.2 Methods

In an in-depth review, Tiller et al. (2019) recognized the lack of information and thus related consequences of OA on the economically important species. As such, we have focused our investigation of OA-related sensitivity on the most economically important species, *Mytilus galloprovincialis*, with the most studied OA impact (Zunino et al. 2017), showing negative sublethal response related to calcification at pH = 7.7. This value represents an early warning threshold for OA impacts.

The risks associated with fisheries in the Mediterranean are related to two factors. First, the direct, specific fish *sensitivity*, and second, the *sensitivity* and the *exposure* of the biogenic habitats which are important nursery and foraging habitats for a variety of fish in the coastal habitats (Zunino et al. 2021).We focus only on a variety of surface to near-surface biogenic habitats that show high pH sensitivity, on average at pH = 7.8, which is a value that can induce sublethal responses related to the reduced growth, calcification, and increased dissolution of many coastal biogenic habitat builders, and is lethal to red coral (Cerrano et al. 2013). To describe current and future levels of *sensitivity*, species representative of aquaculture activities with well-defined sensitive pathways occurring at specific OA thresholds can be used. Such information on thresholds was overlaid with current and future pH exposure maps to understand spatial patterns of OA risks.

A comparison of carbonate chemistry parameters (pH and aragonite saturation state, Ω_{ar}) distributions in summertime (July–September) 2019 and 2100 has been conducted across three different depths, i.e. 26, 51, and 250 m. The three depth levels were chosen to represent the habitats that various pelagic and benthic species inhabit and form respective ecosystems. Present day estimates (summer 2019) of seawater pH, dissolved inorganic carbon, chlorophyll a, salinity, and temperature have been derived from the European Copernicus Marine Environment Monitoring

Service (CMEMS; Bolzon et al. 2020; Clementi et al. 2019) at 1/24° of horizontal resolution.[5]

The projected pH values under RCP 8.5 scenario for 2100, are derived from the analysis made with the coupled physical-biogeochemical model OGSTM-BFM, 1/8° horizontal resolution (Solidoro et al. 2022). The average sea surface temperature (SST) and sea surface salinity (SSS) are projected to increase 3 °C and 0.5 respectively by 2100. Projected changes of pH in the Mediterranean basin are −0.34 pH units in the first 500 m, decreasing to −0.20 and −0.15 pH units in the 500–1000 m 1000–5000 m depth layers respectively. These values agree with the values (around 0.352 pH unit, range 0.242–0.462) from Adloff et al. (2015), Goyet et al. (2016), Richon et al. (2019), and the one projected by Feely et al. (2009) for the North Atlantic and North Pacific. The aragonite saturation state (Ω_{ar}) has been estimated from total alkalinity (μmol/kg), DIC and pH, using CO2SYS (Lewis and Wallace 1998). The 2100 projections of DIC and other carbonate chemistry variables were calculated with CO2SYS using the pH, temperature, alkalinity and salinity of 2019 CMEMS datasets corrected by the basin average projected changes of pH in agreement with Solidoro et al. 2022 (other variables have kept constant). The projected increase in temperature and salinity resulted in a small increase in Ω_{ar} of about 0.04 units.

18.3 Results

18.3.1 pH and Ω_{ar} Distributions in 2019 and 2100

There are notable spatial and vertical pH gradients across the Mediterranean basin under the current (2019) and expected OA conditions in 2100 (Fig. 18.1). A significant finding is the occurrence of lower pH values at 26 m depth, when compared to the 51 m or even the 250 m depth. This could be due to the highest temperature values in shallow waters presented in Fig. 18.2. The northern part of the Western Mediterranean, mid-Adriatic, and Aegean side generally have the highest pH values, ranging between pH of 8.0 and 8.13. The southern part of the Mediterranean basin is characterized by the lower pH values (pH range: of 8.0–8.05), with the coastal regions along the African coast, the Gulf of Gabes, the Libyan Sea (Central Mediterranean) and the coastal Levantine Sub-basin (South-Eastern Mediterranean) having the lowest pH values (about 7.96–7.99). Low pH values in offshore waters appear mainly in the Algerian-Balearic Sub-basin (Western Mediterranean), Southern Ionian Sub-basin, and the Western side of the Adriatic Sub-basin. In these same regions the coastal trend of low pH surface water is extended towards the offshore waters. Significant north-south pH differences are still observable at the depth of 51 m, examples including the Sea of Crete and in the Gulf of Iskenderun. In

[5] https://resources.marine.copernicus.eu/product-detail/MEDSEA_MULTIYEAR_PHY_006_004/INFORMATION

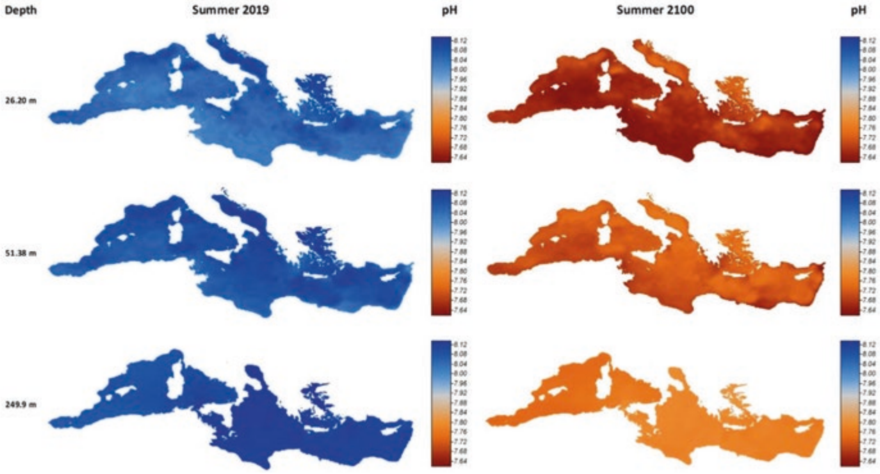

Fig. 18.1 Spatial distribution of pH for (**a**) July–September of 2019 (Bolzon et al. 2020) and (**b**) 2100 in the Mediterranean basin at three specific depths

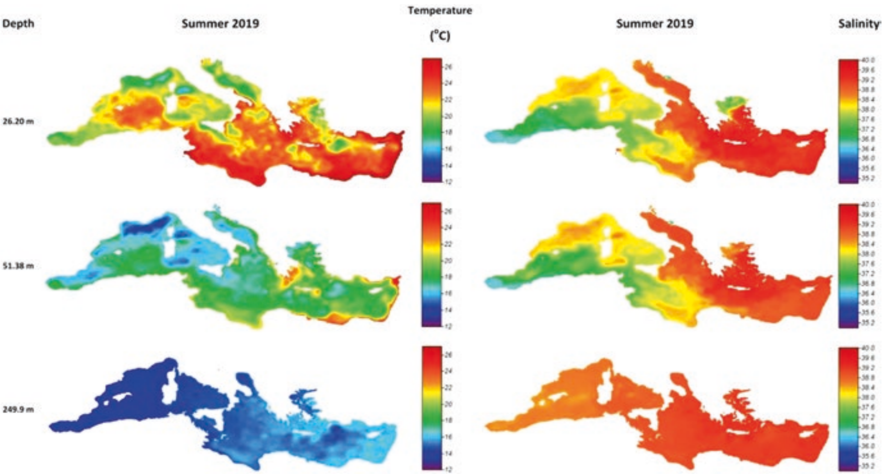

Fig. 18.2 Spatial distribution of (**a**) seawater temperature (°C) and (**b**) salinity for summer 2019 in the Mediterranean basin. (Clementi et al. 2019) at three specific depths

contrast, at 250 m depth, major pH gradients are more prominent in the west- east direction, with the Western basin having slightly lower pH values (range: 8.00–8.05) compared to the Eastern basin (range: 8.05–8.13), with the north-south pH gradient no longer apparent at 250 m. The pH projections for 2100 demonstrate the same spatial patterns as under the current (2019) conditions, with the lowest pH values in the upper 26 m projected for the Ionian Sub-basin and the eastern part of the Tyrrhenian Sub-basin. The projected frequency histogram of pH conditions for 2100 in the entire Mediterranean Sea ranges from 7.64 to 7.74 (Fig. 18.3). The 2100

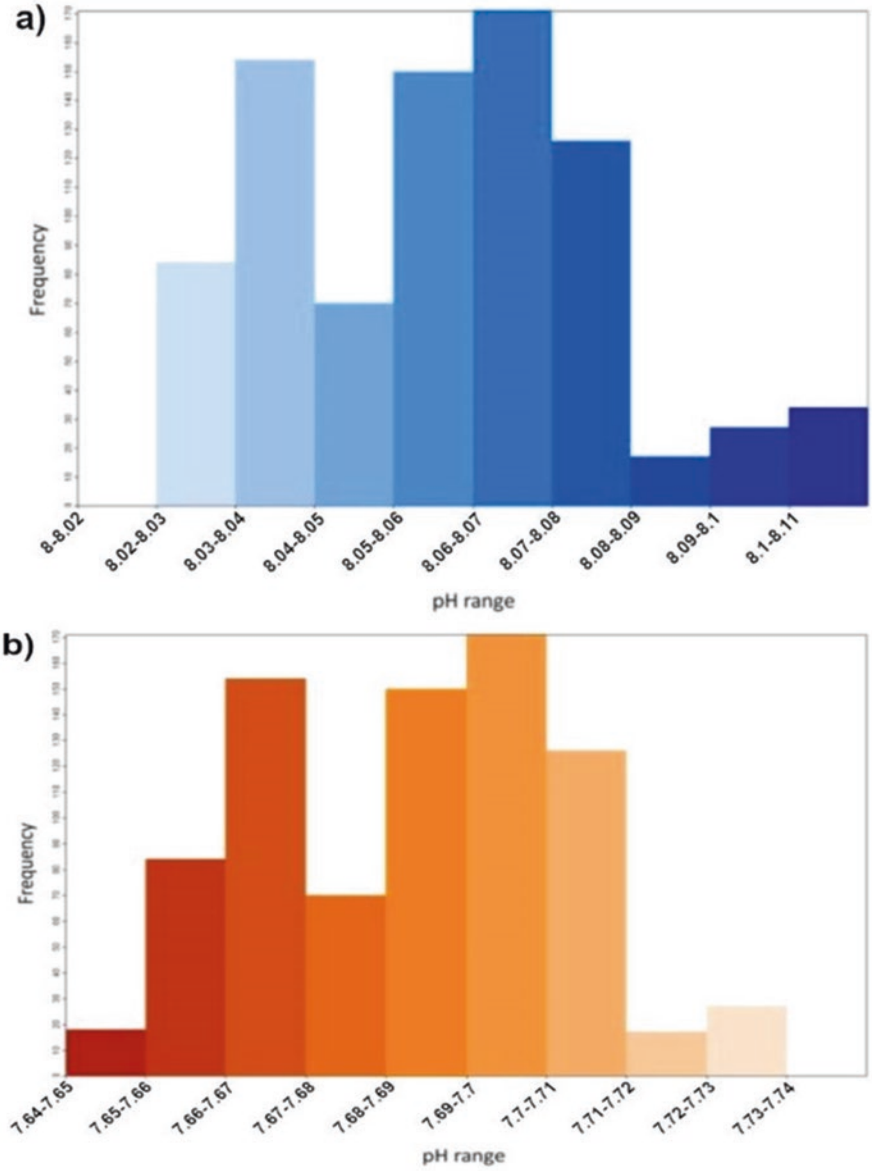

Fig. 18.3 Frequency histogram showing the pH range found within aquaculture shellfish installations in the Mediterranean (N = 335) for summer 2019 (left, blue) (Bolzon et al. 2020) vs. 2100 (right, orange) at depth of 26 m. Discrete pH classes (based on an offset pH value of −0.36 on 2019 values; Table 1) for 2019 are plotted against the number of shellfish installations

pH distribution at 50 m depth shows more uniform values across the entire sea, representing an important difference from present-day conditions. Based on the 2100 projections, it appears that the regions with currently high pH values will acidify faster than the regions with lower values. At 250 m depth, the observed pH gradient is greatly reduced, with pH values slightly higher in the Eastern basin.

The Ω_{ar} horizontal distributions for summer 2019 are roughly inversely correlated with pH, while the projected 2100 patterns generally look more uniform (Fig. 18.4). An important difference in Ω_{ar} compared to pH is that Ω_{ar} values are the highest at 26 m and consistently decrease at 51 and 250 m depths. There is a characteristic west-east Ω_{ar} gradient at 26 m depth, with the Western having lower values ($2.4 < \Omega_{ar} < 3.2$) compared to the Eastern basin ($3.4 < \Omega_{ar} < 4.3$). The regions with the highest current Ω_{ar} values are in the Aegean, coastal Levantine, Adriatic, and coastal central Mediterranean sub-basins. Although there are lower Ω_{ar} values at 51 and 250 m depths, the west-east gradient in Ω_{ar} still exists, but it is not as apparent. The 2100 projections show reduced Ω_{ar} gradient at all depth levels. Near the surface, Ω_{ar} values decrease more in the Eastern than in the Western basin, while at 250 m, the Western basin contains lower Ω_{ar} values closer to the saturation state ($1.3 < \Omega_{ar} < 1.7$) compared to the range of Ω_{ar} values ranging from 1.7 to 1.9 in the Eastern basin.

18.3.2 Assessment of the Risks Related to the Aquaculture

Here, we define *vulnerable* regions as areas associated with increased risk due to ocean acidification; specifically, the combination of OA exposure and the species sensitivity (*sensu* Bednaršek et al. 2021). Estimation of *exposure* was applied to the

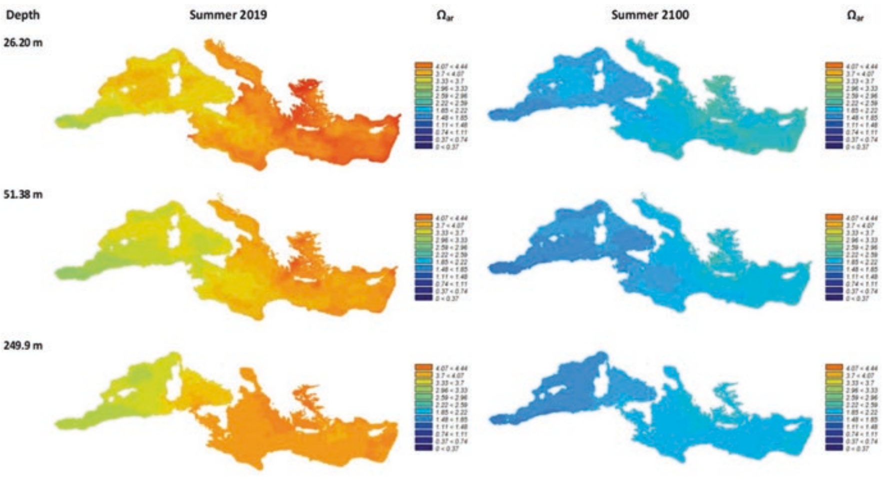

Fig. 18.4 Spatial distribution of aragonite saturation state (Ω_{ar}) for (**a**) summer 2019 and (**b**) estimated 2100 in the Mediterranean basin at three specific depths (26, 51, and 250 m)

regions of intense aquaculture activities occurring in coastal areas from the surface to 20 m depth. Spatial location of aquaculture sites used for this study were derived from the European Marine Observation and Data Network (EMODnet, Human Activities 2020; Fig. 18.5), which represents the most comprehensive database connected to the network of organisations committed to provide accurate biogeographic information and tightly coupled to the EU's integrated maritime policy. Spatial mapping of these sites shows installations located mainly along the Mediterranean shores of France, Italy, and Greece. However, EMODnet states that the absence of other locational information does not mean the absence of such installations, only indicating that the information on the aquaculture is very fragmented, especially in the southern shores of the Mediterranean.

The areas with dominant aquaculture activities are currently in the regions with the highest summertime pH range (8–8.1) in the upper 20 m. Of these, the lowest baseline pH surface conditions occur in the western part of the Ionian Sub-basin, as well as the eastern part of the Tyrrhenian Sub-basin. Under current pH conditions, exposure in all of the aquaculture-intense regions is well above the thresholds associated with physiological impairments (pH = 7.7), based on which we conclude that there is no current risk for the aquaculture. Conversely, the future (2100) RCP 8.5 summertime scenario projects a considerable decline in suitable conditions and, thus, increased exposure to conditions below the pH thresholds across all of the regions occupied by aquaculture installations. With an average projected pH value of 7.65, exposure will be consistently below the thresholds, likely impairing

Fig. 18.5 Regions with intensive aquaculture sites, identified by the European Marine Observation and Data Network, from which 2019 and 2100 pH projections were derived in this study

essential pathways, such as calcification, growth, acid-base regulation, etc. Based on this assumed increase in exposure (Fig. 18.1) and associated sensitivity, the risk for the aquaculture industry is expected to significantly increase under the 2100 scenarios, although this level of exposure would still not induce an increased mortality linked to the substantially lower pH values.

18.3.3 Indirect Risk of OA on the Fisheries in the Mediterranean Sea

In this study, we indirectly evaluate fisheries risks to OA through the *exposure* of the biogenic habitats serving as an essential fisheries habitat. The outputs were specifically related to the near-surface vertical habitats in coastal regions for the upper surface 10–20 m depth for the entire Mediterranean Sea. The lowest summer pH surface conditions, down to pH = 7.96, occur in the eastern part of the Tyrrhenian Sub-basin, the entire Eastern Mediterranean coast around the Levantine Sub-basin, the central North African coast, the southwestern Mediterranean coast, and the northern Adriatic Sub-basin, with the sole exception of the Aegean Sub-basin (Fig. 18.1). These conditions are very near the pH threshold of 7.8–7.9 that can induce negative impacts of the biogenic builders, exposing these habitats to below the thresholds fairly frequently in the summertime even under present-day conditions, especially when the duration of the exposure is the longest. Given that the 50 and 250 m pH values are higher indicating that the risks for this deeper depth biogenic habitats are lower.

Based on the future pH projections, the risk for the biogenic habitats is expected to substantially increase under future (2100) RCP 8.5 scenarios where summertime conditions below the threshold of pH = 7.8 are uniformly present over the entire Mediterranean Sea at the 10–20 m depth, with no sub-basin spared. Even the deeper depth builders at 50 m will be exposed to conditions below these thresholds, indicating that not only spatial but also vertical fisheries habitats will be compromised.

18.4 Shaping Adaptive Management Options to Combat OA in the Mediterranean Sea

Lessons from the past, including but not limited to "the aquaculture failure" (Barton et al. 2012), as well as the literature, show that OA is an emerging, complex challenge requiring polycentric and feasible nature-based solutions at the climate-OA-biodiversity nexus (*sensu* Turley et al. 2010; Galaz et al. 2012; Billé et al. 2013; Gattuso et al. 2015, 2018). Although OA is global by essence, its consequences fall asymmetrically upon respective ecosystems and the coastal and local communities that depend on them (Osborn et al. 2017). Therefore, there is indeed a need to develop context-dependent management strategies to minimise ecosystem damage caused by the continued release of CO_2 (Albright et al. 2016). Earlier in the text, we assessed the risks related to the aquaculture and fisheries under current and future conditions in the Mediterranean Sea. Such broader risk characterisation over the wider Mediterranean basin is useful in understanding regional OA hotspots and the ecosystem service sensitivity and establishes when and where OA mitigation or adaptation measures are needed. Such approach also identifies an explicit link with the adaptive governance by highlighting the core role of continued and context-based scientific assessment in decision-making.

There are currently no direct and structured regulation of OA, either internationally or for the Mediterranean Sea. The long-lasting socio-ecological effects of OA are embedded in a highly diffuse and complex regulatory and institutional framework, without any topic-related institution, mechanism, or mandate to combat it, across geographical and temporal scales, or "scale-independently" (Galdies et al. 2020; Billé et al. 2013). The difficulty in communicating with both decision-makers and stakeholders contributes to a regulatory gap in developing targeted regulatory frameworks and setting statutory pH thresholds. Barriers to generating data and information also explain why interactions between regimes pertaining to OA (for instance, climate, biodiversity, and ocean regimes) are primarily cognitive and epistemological, rather than normative and institutional.[6] Other non-OA specific impediments exist, such as mismatching institutional and legal frameworks, geopolitical tensions between riparian states, the lack or unequal distribution of resources or capacity, the lack of will and commitments of actors or pathway dependency (*sensu* Berkowitz 2020).

Several state and non-state actors have worked on the issue in recent years, mostly through informal or mixed initiatives aimed at creating awareness around the problem, synthesising and disseminating scientific information, and influencing negotiations at high-level forums.[7] Substantial outcomes, in terms of governmental action to implement concrete policies and policy tools with the capacity to generate behavioural change necessary to prevent OA, are still largely unseen (Galaz et al. 2012; Osborn et al. 2017; Ziveri et al. 2017; Jagers et al. 2019). The governance of the Mediterranean remains somehow ill-adapted to OA, without any strong dedicated or integrated policies, clear institutional mandates, or legally binding objectives, thus resulting in slow and uncoordinated progress. This issue is compounded by a linear, deterministic and state-centric approach that is still reflected in international law and governance and is unsuited to the necessary systemic vision of OA as a boundary challenge (*sensu* Capra and Mattei 2015; Rockström et al. 2009).

In light of the projected impacts of OA on marine habitats and ecosystems, as well as the fisheries and aquaculture provisioning services and other ecosystem regulating and supporting services, "best possible futures" regarding OA in the

[6] For more information, see Guilloux (2020).

[7] Cicin-Sain et al. (2019, p. 20); Ocean alliance to combat ocean acidification: https://www.oaalliance.org/; Global Ocean Acidification Observing Network (GOA-ON) and its Ocean Acidification Mediterranean Hub (OA Med-Hub); Ocean Acidification International Coordinating Centre of the IAEA (International Atomic Energy Agency).

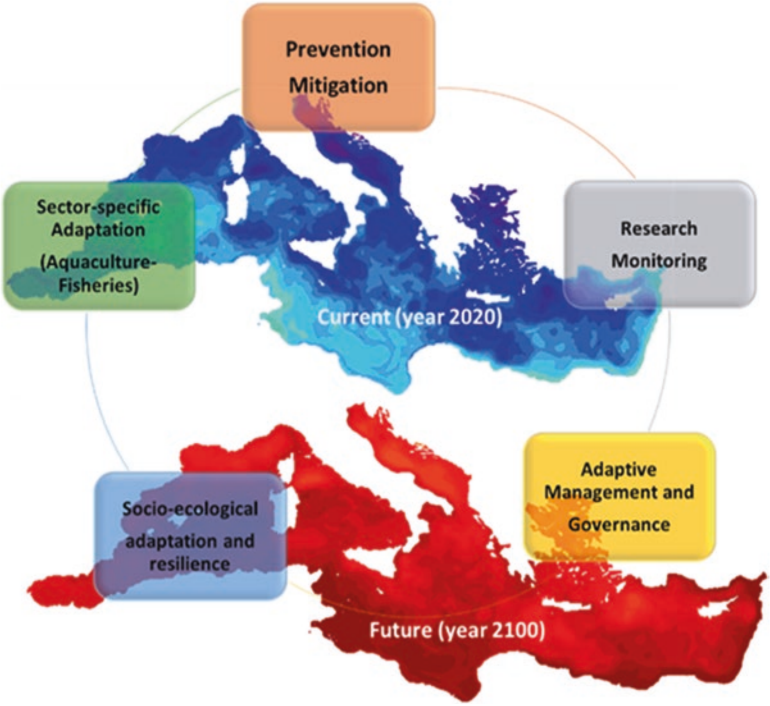

Fig. 18.6 Linkage of socio-ecological system to transition between current (2020) and future (2100) pH conditions

Mediterranean Sea and its sub-basins requires a bundle of interconnected strategies (Fig. 18.6), overall related to the central framework of an *Adaptive Management and Governance.*[8] Such framework includes the *Adaptation and Resilience* (improvement of the capacity of adaptation and resilience of the changing Mediterranean socio-ecological system to OA impacts); V*isionary research and Monitoring* (transcending disciplinary as well as political and legal divides and projecting to spatial and temporal scales adapted to socio-ecological issues); and finally *Prevention* (in the form of rapid and complementary global-scale reductions in greenhouse gases (GHGs), especially CO_2, and local reduction in anthropogenic sources of OA).

[8]Adaptive governance is a system of environmental governance with the potential to mediate the complexity and uncertainty inherent in socio-ecological systems (Dietz et al. 2003; Walker et al. 2004; Folke et al. 2005; Folke 2006), whereas adaptive management implies acknowledging uncertainty (and complexity) through prudent decision making rather than a static "answer" (or failure to act) by continuously gathering and integrating appropriate ecological, social, and economic information and knowledge with the goal of adaptive improvement (sensu Walters 1986, 1997; Costanza et al. 1998; Gunderson 1999; Lee 1999; Dietz et al. 2003; Chaffin et al. 2014; Monaco Ocean Acidification Action Plan, Priorities (5), 2018, p. 2).

Besides linking knowledge and decision-making through data collection and monitoring, meaningful and effective coordination and cooperation between states and non-state actors, capacity development, and exploiting governance and legal opportunities seems to be the most relevant options contributing to adaptive governance to combat OA in the Mediterranean (Sharma-Wallace et al. 2018). The side-by-side model of governance and institutional polycentricity, redundancy, and diversity (EU, Barcelona, and regional fisheries institutions) can be a premise towards adaptive governance (sensu Dietz et al. 2003; Galaz et al. 2012; Chaffin et al. 2014).Adaptive governance cannot be reduced to a list of specific prescriptions, but instead rests on situated "pattern of practises" (Brunner et al. 2005) of state and non-state actors towards common goals and behaviours in addressing OA impacts and related risks. It culminates in coordination at the bioregional scale, a scale at which the governance structure best fits ecological functions (Olsson et al. 2007; Huitema et al. 2009; Termeer et al. 2010; Cosens 2013; Chaffin et al. 2014) but has yet to find a common socio-anthropological meaning.[9] Matching regional and local governance scales is a challenge for tailored management actions to address OA. Given that EU and Mediterranean institutions (e.g., the coordinating unit for the Mediterranean Action Plan- Secretariat to the Barcelona Convention and its Protocols) might be more robust than global ones, regionally framed multilevel governance may well be an appropriate response to global challenges like OA (sensu Patt 2010; Selin and VanDeveer 2009, 2011). To avoid national policy gaps created by the flexibility of fisheries and aquaculture policies in the Mediterranean (Said et al. 2018), Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs) have so far neglected OA (Gallo et al. 2017). Fisheries (Hidalgo et al. 2018), or aquaculture might be the most adapted tools to address OA in an integrated manner (Galdies et al. 2020). For example, scenario analysis, modelling the effects of emission reductions (Steinacher et al. 2013) should be used to assess global and local impacts of OA of several climate policy responses (IPCC 2019).

Supporting adaptive management and governance to combat OA does not necessarily require the creation of new legal and institutional settings. It depends foremost on improving the adaptive capacity of existing EU and regional policies and laws in changing or even shifting socio-ecological conditions and problems, incorporating incrementally varied actors (regional organisations and non-state actors) and processes for amending and decision-making, without creating instability or rigidity.[10] First, this involves identifying, legal constraints to an adaptive OA management in the Mediterranean and remedy to them: e.g., the "dilution" of SDG 14.3 in sector-based legal and institutional frameworks, politically-economically

[9] Ideally, the scale of adaptive governance will also have to be targeted to the social and ecological nature of the OA problem, as well as to societal goals like SDG 13 or healthy marine ecosystems, through sufficient response flexibility within and between existing political boundaries (Cosens 2010; Termeer et al. 2010; Chaffin et al. 2014).

[10] For more information about the role of Law in adaptive governance, see Ruhl (1997), Cosens et al. (2017), Gosnell et al. (2017), and Reinke de Buitrago and Schneider (2020).

oriented decisions rather than science-based ones, inadequate mandates, jurisdictional overlaps, narrow and prescriptive rules, potentially conflicting principles and norms leading to socio-environmental problem shifting.

Second, existing adaptive processes should also be strengthened to minimise risks and build resilience. OA should thus be factored into adaptive fisheries and aquaculture management plans (Lacoue-Labarthe et al. 2016), whose implementation varies throughout the Mediterranean between EU Member States and non-EU Member States, and, among EU Member States in the application of the reformed CFP and associated Strategic Guidelines on Aquaculture (Corner et al. 2020). It could be factored through pH-associated regime changes, thresholds, or tipping-points (Hughes et al. 2013; Goyet et al. 2016; Good et al. 2018). Regarding aquaculture, there is a strong need to support governance to establish aquaculture activities within a coordinated spatial planning process under an ecosystem approach, based on integrated coastal zone management principles and the establishment of allocated zones for aquaculture (General Fisheries Commission for the Mediterranean–FAO 2018; Corner et al. 2020). The conducted vulnerability study for the aquaculture (obtained for *Mytilus galloprovincialis*) also offer a baseline to help managers and stakeholders assess the reliability and feasibility of aquaculture in a changing sea that can generate undetected and underestimated impacts on the aquaculture sector (*sensu* Martinez et al. 2018). Third, iterative, transdisciplinary, and reflexive learning and decision-making such as marine spatial planning must also be encouraged, allowing decision-makers and stakeholders likely to be affected by OA to communicate their specific needs to researchers and decision-makers, or even participate in the decision-making process. Finally, "more attention should be paid to the potential disconnects between what science tells us is necessary for a healthy ecological system, what society wants from that ecosystem, and perhaps more importantly, what is politically feasible" (Chaffin et al. 2014; see also, Wyborn 2015).

18.4.1 Fostering the Adaptation and Resilience of the Mediterranean Socio-Ecological System to OA

At their infancy, general and sector-specific adaptation actions are mostly directed at restoring or protecting the production of services and goods harmed by OA ("supply-side oriented") (Ziveri et al. 2017). They focus on treating the localised symptoms of OA where institutions are already in place by adjusting the socio-ecological system (Jagers et al. 2019). These actions or strategies can be applied in an anticipatory (resisting change) and responsive (abating or recovering from change) ways (Billé et al. 2013; Gattuso et al. 2015). They mostly rely on sector-specific adaptation management options, especially in aquaculture and fisheries, such as relocating fisheries and aquaculture activities, and protecting food supply at local, state, and sub-regional levels.

Other targeted and interconnected bundles of solutions can be considered:

- Revisit estimation of OA into monitoring and ecosystem assessments, including how fishing grounds may impact or be impacted by OA. This means including indirect effects on the biogenic habitats that provide spawning and nursery grounds, for which little information is currently available;
- Determine the regions with more suitable future marine pH conditions and strategically invest in aquaculture operations in those regions, select resistant strains more tolerant to OA through selective alternative breeding techniques (Cooley and Doney 2009; Albright et al. 2016; Ziveri et al. 2017), and develop transportable or seasonal aquaculture infrastructure;
- Substitute and diversify fish and aquaculture species when permanently or temporarily possible by compensating fishermen and fish farmers, providing transitional support, and stimulating innovation to accelerate emergence of alternatives and technical replacement solutions (Jagers et al. 2019);
- Sustain food security by cutting or eliminating subsidies in order to reduce incentives to overexploit marine living resources, publicly investing in activities that include protecting the marine environment or supporting fishermen, where decoupling the economy from fishing is the extreme option (Ziveri et al. 2017);
- Develop adaptive and climate-friendly fisheries management so as to be able to incorporate new and emerging knowledge quickly or regularly at the level of RFMOs and the EU (*sensu* Rayfuse 2012; Herr et al. 2014); Modernise the CFP through, e.g., adapting quotas and management systems to OA; Invite RFMOs to promote stronger calls for emission reduction commitments (Herr et al. 2014).

With a view of integrated environmental, coastal and marine policies, the capacities of adaptation to and resilience under OA conditions for the Mediterranean socio-ecological system need to be activated by, *inter alia*:

- Fostering social resilience, which implies addressing the socio-economic impacts of OA by, e.g., breaking down financial, informational, cognitive, social, and cultural barriers; path dependency; compensating vulnerable coastal communities and helping them adapt to their new circumstances by stimulating education and investment; raising public awareness to change people's preferences and habits; linking adaptive environmental management to social transformative needs; etc.
- Supporting ecosystem resilience by:
  - Incorporating OA and other climate-related thresholds, goals and strategies (e.g., nature-based solutions including ecosystem-based approaches) and goals into marine spatial planning, or marine protected areas (MPAs) to conserve or restore species and ecosystems vulnerable to OA. The benefits of such actions are manifold, i.e., they address many stressors simultaneously, act within single jurisdictions or regions, and minimise transaction costs (Billé et al. 2013);
  - Treating fresh- and coastal waters (e.g., for high-value aquaculture by exploiting shellfish production) to support healthy marine waters (Ziveri et al. 2017);

  - Restoring degraded "blue carbon" ecosystems (e.g., seagrass meadows), as well as other ecosystems (e.g., estuaries inhabited by oysters), with the understanding that it may slow long-term changes at the local level but can also exacerbate short-term variability (Sabine 2018);
  - Embedding networks of MPAs, and combining OA exposure with biodiversity and ecosystem functioning, including connectivity, producing a multi-layered, holistic conceptual space that will be instrumental for future management and protection of such networks and of marine environments in general.

- Paving the way for legal and institutional resilience (*Á propos* institutional resilience, Rayfuse 2012; or comprehensive legal approaches, Galdies et al. 2020)

18.4.2 Visionary Research and Monitoring of OA Impacts on the Mediterranean Sea

OA is among the key research questions for biodiversity sustainability and conservation. There is a persistent need for cyclical, interdisciplinary, and long-term OA information sharing and learning to address the complex, uncertain, and technical nature of this ever-widening, transboundary phenomenon (Fig. 18.6). In general, most research on OA has been conducted in the natural sciences on understanding its ecological and biogeochemical implications.[11] Against this background, it is essential to encourage interdisciplinary research on OA in the social, economic, political, and legal sciences, and between social, natural sciences and humanities. Analysing the coherency and conflicts between national, regional Mediterranean and international legal and administrative systems is of critical importance for social (including legal) sciences research with regard to OA (Jagers et al. 2019). A lack of scientific understanding of ecological interdependencies makes it more difficult to detect, avoid, and solve potential legal conflicts (Wolfrum and Matz-Lück 2003) and governance issues. The pace of decision-making partly depends on whether the type or abundance of information being offered from the bottom-up matches what is being sought from the top down (Cooley et al. 2015).

[11] See the *European Mediterranean Sea Acidification in a Changing Climate* (MedSeA) project's key documents available at: http://medsea-project.eu/outreach/key_documents/ [Accessed May 22, 2020]. See also the *European Project on Ocean Acidification* (EPOCA) funded by the European Commission under Framework Programme 7 from 2008 to 2012. For more information, see European Project on Ocean Acidification | EPOCA Project | FP7 | CORDIS | European Commission. Available at: https://cordis.europa.eu/project/id/211384 [Accessed May 22, 2020]. OA is also amongst the indicators of the Environmental Europe Agency, designed to answer key policy questions and to support all phases of environmental policy making. For more information, see Ocean acidification European Environment Agency. Available at: https://www.eea.europa.eu/data-and-maps/indicators/ocean-acidification-2 [Accessed May 22, 2020].

For instance, there is a lack of empirical and context-specific knowledge evaluating the resilience and adaptive capacity of legal systems to climate, biodiversity, and ocean changes. There is also a need for the provision and the communication of reliable information (long-term data, datasets, models, standards, and observational networks) aligned with the level of understanding of local stakeholders and policy makers, and their expectations and with pre-existing priorities related to climate and regional development (Cooley et al. 2015). Such alignment is paramount in order to secure the scale of investment, to develop forecasting capabilities (Monaco Ocean Acidification Action Plan, Priority No 6), and to move forward transdisciplinary and precautionary marine spatial planning (Fig. 18.6). Ideally, relevant socio-anthropological and governance information and knowledge should be integrated to guide the way best available science on OA is produced and used in decision-making. The following are suggested for an improved evidence-based decision-making:

Support of integrated *in situ* scientific information supply, monitoring and modelling to enable better-informed decision-making:

- Continuous, local carbonate chemistry monitoring (of at least two carbonate system parameters); Characterising seasonal patterns; Monitoring and understanding processes related to coastal pH variability;
- Continue researching economically important species and scale up to the ecosystem level, and the potential synergism of acidification with other climate change relevant stressors, including warming and marine heat waves, stratification, and eutrophication.
- Devise long-term experimental studies to understand adaptation as well as acclimation (Monaco Ocean Acidification Action Plan, Priority No 2).
- Strengthen regionally and financially incentivise a coordinated and institutionalised network of monitoring stations through the OA Mediterranean hub[12] of the Global Ocean Acidification-Observing Network (GOA-ON), to map the vulnerability of coastal areas to OA and to extend monitoring to near-shore systems relevant to management jurisdictions;

Definition of interdisciplinary research priorities and frameworks (*sensu* Albright et al. 2016) such as:

- Direct and indirect effects of OA on spawning and nursery habitats and their consequences on fisheries;
- Identify critical habitats sites (*sensu* Ziveri et al. 2017) based on the most ecologically critical and sensitive bases; as well as heavily under-studied Mediterranean areas, such as the South and South-East realms that might be negatively exposed to OA and would benefit from strong research coordination, building capacity and OA-related policy and management;

[12] For more information, see http://www.goa-on.org/regional_hubs/mediterranean/about/introduction.php [Accessed May 22, 2020].

- High-resolution physical-chemical observations and regional downscaled model outputs should be used to provide more accurate and spatially explicit OA exposure.
- A governance structure that enables continued support for the further development and use of downscaled models and significant enhancement of coastal observation processes will help understand local and regional processes, their timing, and extent that can negatively impact ecosystem services, and result in improved management-policy actions.
- Set up initiatives in each EU coastal State to assess the threat of OA to ecosystem health and human livelihoods and to evaluate strategies to mitigate local drivers (*sensu* Strong et al. 2014);
- Identify and financially support interdisciplinary research related to the socio-ecological impacts of OA or evaluating the adaptive capacity and the resilience of regional governance systems, to slow onset and abrupt environmental changes within the next research and innovation framework programme (Horizon Europe).

18.4.3 Preventing OA by Mitigating Climatic and Anthropogenic Sources

The only comprehensive solution to prevent further OA is to rapidly and drastically reduce global anthropogenic emissions of CO_2 and other GHGs uptake by the ocean. Multi-level policy tools targeting CO_2 emissions and beyond, behavioural changes, exist such as the EU climate action and the European Green Deal.[13] They are not designed to address OA specifically but can be marginally adapted to do so (Billé et al. 2013; Jagers et al. 2019) and to embrace the sustainable development and biodiversity post 2020 goals. In addition, where local and national economies rely heavily upon carbonate-dependent ecosystem services like in the Mediterranean Countries, reducing local acidifying stressors could produce results both faster and in a more politically feasible manner than at the global level (Billé et al. 2013; Gattuso et al. 2018). Such reductions could include non-atmospheric local or site-specific stressors, such as nutrient pollution (nitrogen, phosphorus) and runoff from acidic fertilisers used in agriculture (Doney 2010; Kelly et al. 2011; Carstensen et al. 2020; Duarte et al. 2020).To this end, a spatially explicit biological vulnerability assessment (as conducted in here), and the inclusion of different stakeholders of relative importance to the different causes related to OA is necessary to maximise the utility of smaller-scale policy recommendations (Billé et al. 2013; Galdies et al. 2020).

[13] For more information, see Cabuzel (2019).

18.5 Critical Considerations

The biogenic habitats that are uniform coastal features across the Mediterranean basin are and will be more severely impacted in the future, especially in the less developed areas around the Mediterranean coast. Currently, despite being on the list of endangered or vulnerable habitats, there are no specific conservation actions in place for them. Because of such an invaluable habitat role and their sensitivity, marine conservation planning should be considered with regional OA impact in mind. While we address regional ecological risks related to the ecosystem services, we only partially address socio-economic risks, more comprehensively described in Hilmi et al. (2014). The subsistence of human communities depends heavily on marine resources, especially from the less developed Mediterranean nations, where fishing provides a greater contribution to GDP and supports higher levels of employment. Since the majority of fishers fall into the small-scale artisanal category, this makes them more dependent on coastal inshore waters and, thus, vulnerable to the local ecosystem conditions. Concurrently, our risk estimates point towards the coastal ecosystems, such as fisheries-supportive habitats, that will be mostly impacted by OA in the very near future, thus exposing already vulnerable fishing communities even further. This is in contrast to the aquaculture industry stationed in the developed part of the Mediterranean Sea that is, through proactive OA risk management, less vulnerable than artisanal fishers. Still, large adaptation in aquaculture practises and related costs will be needed to sustain the expected increases in productivity that has quadrupled in the last 30 years (Hilmi et al. 2014).

Regional governance on a pan-European and Mediterranean scale has potential to support the development of 'localised' management strategies to minimise the exposure and risks incurred by coastal and marine ecosystems and dependent local communities to the continued release of CO_2 and subsequent OA. The future governability of OA (*sensu* Gattuso et al. 2018) will depend on the robustness, adaptability, and the quality of polycentric (interagency and institutional) coordination (*sensu* Galaz et al. 2012) amongst regional organisations and other non-state actors, while remaining inexorably limited by the global nature of the OA boundary challenge that requires Earth scale-fitted solutions. The most urgent one is the drastic reduction in GHGs/CO_2 emissions (Harrould-Kolieb and Herr 2012; Kim 2012; Herr et al. 2014; Stephens 2015). Despite existing adaptive management tools (e.g., MPAs) and processes (e.g., integrated coastal zone management or marine spatial planning), evaluations of the planning, decision-making, implementation, monitoring, and reporting related to OA are scarce. More extensive learning and experiments are necessary to foster the adaptive capacity of Mediterranean socio-ecological system to abrupt and slow-onset climate and non-climatic changes, to scrutinise potentially maladaptive incentives, mechanisms, and investments, to resort to mass mobilisation to increase OA awareness and, to acknowledge legal and institutional barriers.

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