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Article

Exposure of Mediterranean Countries to Ocean Acidification

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Abstract: This study examines the potential effects of ocean acidification on countries and fisheries of the Mediterranean Sea. The implications for seafood security and supply are evaluated by examining the sensitivity of the Mediterranean to ocean acidification at chemical, biological, and macro-economic levels. The limited information available on impacts of ocean acidification on harvested (industrial, recreational, and artisanal fishing) and cultured species (aquaculture) prevents any biological impact assessment. However, it appears that non-developed nations around the Mediterranean, particularly those for which fisheries are increasing, yet rely heavily on artisanal fleets, are most greatly exposed to socioeconomic consequences from ocean acidification.

Keywords: fisheries; aquaculture; ocean acidification; Mediterranean Sea; economic development; multidisciplinary study

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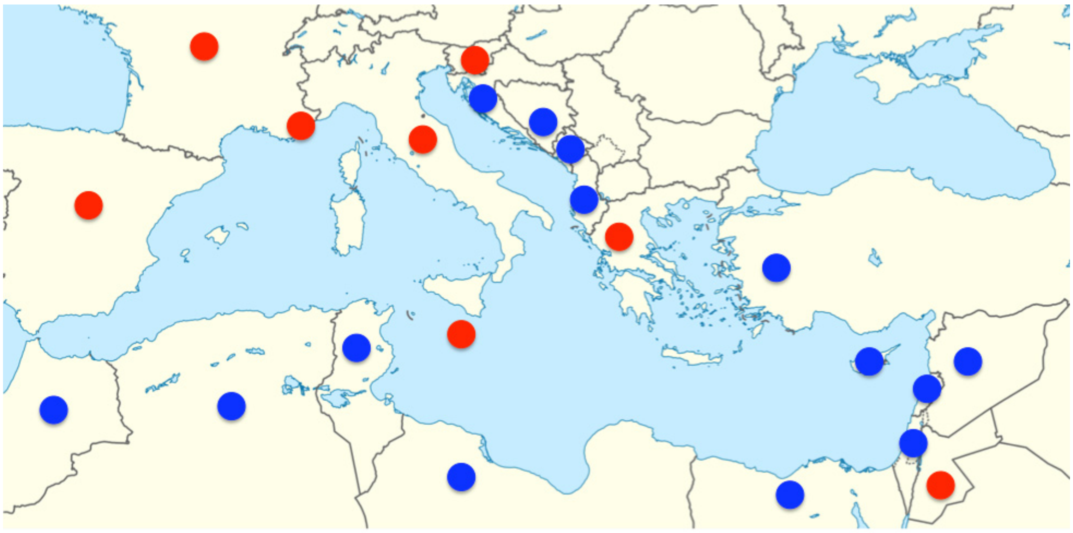
1. Introduction

The semi-enclosed Mediterranean Sea combines densely settled human communities, vast marine biological diversity and productivity, and progressive environmental change, making it an interesting place to study the complex linkages between human and marine ecological systems. Twenty-one countries of varying economic developmental status on three continents, Africa, Asia, and Europe, surround a 26,000-km coastline with an estimated 465.5 million inhabitants (Figure 1). The Mediterranean Sea covers only <0.8% of the world ocean's surface and includes <0.3% of its volume, but it is home to an unusual amount of biodiversity for a temperate sea [1]. About 17,000 species live there, *i.e.*, 4%–18% of the world's recorded species [2]. Environmental threats from human activities are manifold, including those from intensive fishing, eutrophication, untreated sewage, heavy shipping traffic, marine litter, and introduction of alien species [2]. The increase in coastal population and the large number of tourists to the region, attracted by its many cultures and pleasant climate, place additional pressures on the ecosystem [1]. Layered atop these very localized pressures are progressive global-scale changes that also affect the entire Mediterranean Sea, such as ocean warming and ocean acidification.

Ocean acidification is the long-term change in ocean chemistry caused by increasing atmospheric CO_2 from combustion of fossil fuels, deforestation, and cement production. The global ocean currently absorbs about one-fourth of the anthropogenic CO_2 that is emitted to the atmosphere [3], which, when combined with water, produces carbonic acid and thereby releases hydrogen ions. Some of the hydrogen ions produced are consumed by reacting with naturally abundant carbonate ions. Thus, ocean acidification increases hydrogen ion concentration $[H^+]$, sometimes called acidity, and decreases pH (defined as $-\log[H^+]$) and carbonate ion concentration. The decrease in carbonate ion concentration leads to a decrease in the saturation state of calcium carbonate minerals (Ω) like aragonite and calcite; saturation states are common metrics used to track ocean acidification. Ocean acidification is irreversible on the scale of at least hundreds of years [4].

Ocean acidification is expected to adversely affect many marine organisms, including some commercially important species, either directly or indirectly. Ocean acidification may affect marine species directly by altering organism physiology. Ocean acidification may also operate indirectly by disrupting food webs or altering physical habitats, which in turn may affect other harvested species [5]. The impact of ocean acidification on marine species is known to be highly species-specific (e.g., [6,7]), yet meta-analyses and reviews have indicated a general tendency of bivalve shellfish and other calcifiers to demonstrate reduced calcification and survival [4,8,9]. This has been hypothesized to be a result of energetic shortages within organisms, which need to spend more energy building and maintaining hard structures in an acidifying ocean. A handful of studies on unrelated finfish species have identified different behavioral changes related to ocean acidification, such as increased boldness [10,11] or anxiety in Rockfish via alteration of $GABA_A$ receptor functioning [12], whose population-scale effects are not yet known. Whether or not behavioral changes from ocean acidification will be observed across many other finfish species is also not yet known [13]. In addition, how individual organisms' responses to ocean acidification that have been documented in laboratory studies scale up to cause population-scale responses is yet largely unknown.

Figure 1. Map of the Mediterranean Sea (Nordwest, using World Data Base II data) [14]. Developed countries (red circles): France, Greece, Israel, Italy, Malta, Monaco, Slovenia, and Spain. Other countries (blue circles): Albania, Algeria, Bosnia-Herzegovina, Croatia, Cyprus, Egypt, Lebanon, Libya, Montenegro, Morocco, Palestine, Tunisia, and Turkey.



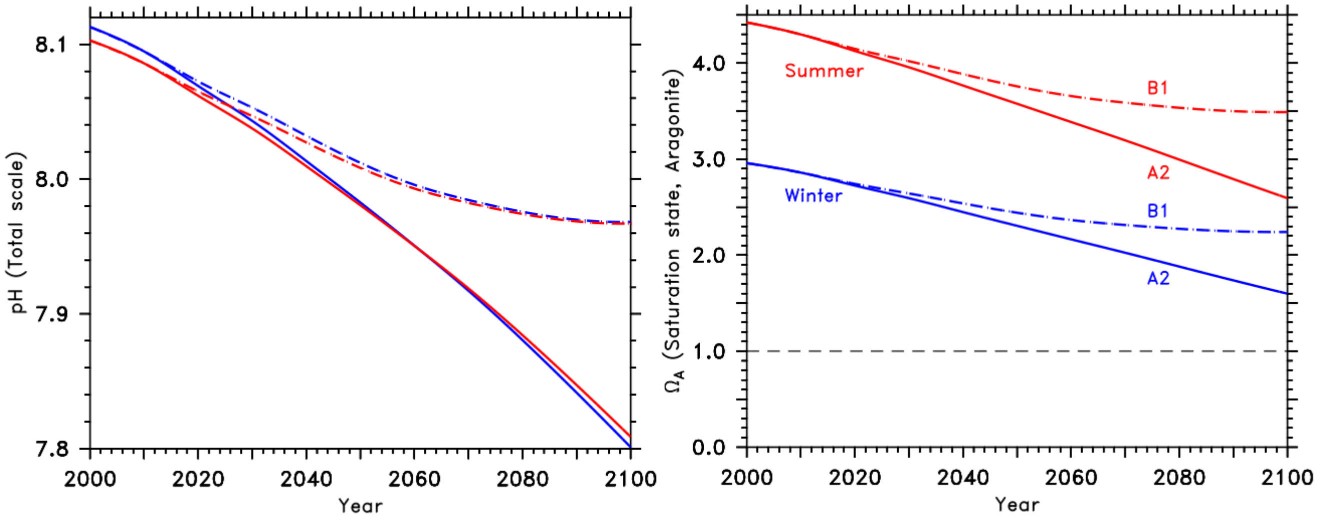
Human communities around the Mediterranean Sea seem very likely to experience changes in marine harvests driven by ocean acidification, given their heavy dependence on marine resources and the certainty that ocean acidification will affect this sea and its species. To assess the total possible risk that Mediterranean communities face from ocean acidification, we must evaluate the intersection of the hazard (*i.e.*, ocean acidification), exposure of valuable assets to ocean acidification, and the communities' vulnerability or adaptive capacity within the social system [15,16]. At present, few studies have reported ocean acidification responses of the most nutritionally or economically important species harvested in the Mediterranean [17]. In addition, the level of dependence of Mediterranean coastal communities on marine harvests is not extremely well known; data at the national level are more easily accessible, which likely obscures some of the local importance of marine harvests. Nevertheless, we can use existing marine harvest data and our present knowledge about ocean acidification responses to assess the exposure of Mediterranean nations to ocean acidification. This paper reviews our knowledge around ocean acidification's possible socioeconomic impacts in the Mediterranean within a risk assessment perspective [16], a method that highlights where more research is needed to completely assess the risk from ocean acidification in the Mediterranean. We begin by reviewing ocean acidification's progression in the Mediterranean, the ocean acidification responses of Mediterranean species, and fisheries harvest data around the Mediterranean. We then estimate the exposure of Mediterranean nations to ocean acidification via fisheries harvests. We then conclude by discussing how the exposure of Mediterranean nations to ocean acidification might be exacerbated or mitigated by social or ecological factors in a full risk assessment.

2. Ocean Acidification's Development in the Mediterranean

The Mediterranean Sea has higher alkalinity than the global ocean, which leads to an ocean acidification response that differs somewhat from that of other regions. Alkalinity refers to the acid neutralizing capacity of the water and should not be confused with alkaline ($pH > 7$). Alkalinity is higher because evaporation is greater than precipitation, and because rivers and the Black Sea provide high alkalinity water to the Sea. It has been proposed that this higher alkalinity causes the rate of acidification of the Mediterranean Sea's surface waters to be larger than that of the global ocean, based on data-based estimates of anthropogenic carbon [18,19]. However, the other data-based methods used to estimate the anthropogenic component of dissolved inorganic carbon in the Mediterranean Sea suggest much smaller changes [20]. Equilibrium calculations from Orr [21] confirm the Mediterranean Sea's greater capacity to take up more anthropogenic CO_2, as well as undergo a greater corresponding reduction in carbonate ion, compared to the global ocean. However, the same calculations demonstrate that the Mediterranean Sea's average change in surface pH will not differ significantly from that typical of the global ocean.

The first estimates of anthropogenic changes in surface pH from high-resolution, regional models of the Mediterranean Sea confirm that at present the average change in surface pH (1800 to 2001) remains indistinguishable from those for typical surface waters of the global ocean, and have little spatial variability across the surface of that semi-enclosed sea [20]. For future trends we must rely on equilibrium calculations because no high-resolution model projections have yet to be published. Thus, we used seacarb software [22], with projected atmospheric CO_2 levels from the Institute Pierre Simon Laplace Coupled Model, version 4 (IPSL-CM4) forced by the Intergovernmental Panel on Climate Change (IPCC) business-as-usual A2 scenario and the more conservative B1 scenario [22] over the 21st century. With that forcing, pH and related carbonate system variables were computed by assuming thermodynamic equilibrium between atmospheric CO_2 and the surface ocean at the Dyfamed time-series station in the northwestern Mediterranean Sea (total alkalinity of 2560 $\mu eq \cdot kg^{-1}$, salinity of 38 on the practical salinity scale, and temperatures of 13 °C in winter and 26 °C in summer, [23]) By the year 2100, surface-water pH is projected to decline by another 0.3 units under the A2 scenario, where atmospheric CO_2 reaches 836 ppm (Figure 2). Under the B1 scenario, the projected change in pH is only about half as much because atmospheric CO_2 is projected to reach only 540 ppm. Under the A2 scenario, the saturation state with respect to aragonite (Ω_A) drops to as low as 1.6 in winter and 2.4 in summer, well below the threshold considered sustainable for tropical corals (e.g., [24]). Extending the same calculations back over the industrial period (1800 to 2000) shows that the Mediterranean Sea's pH has already declined by 0.1 units, consistent with model projections [20]. Simultaneously, the Mediterranean's Ω_A has declined by 0.7 units.

Figure 2. Surface-water pH (**a**) and saturation state with respect to aragonite (**b**) during the 21st century projected for the business-as-usual IPCC scenario A2 (solid line) and the more conservative B1 scenario (dashed line) under typical conditions for summer (red) and winter (blue).



(**a**) (**b**)

3. Known Ocean Acidification Responses of Mediterranean Species

Despite the large number of species harvested in the Mediterranean, the ocean acidification response of a relatively small number of species has been tested. Of the 94 harvested and cultured animal species that are of economic relevance in the Mediterranean (Table A1, data from Food and Agriculture Organization (FAO) data on National Aquaculture Sector Overview [25] and Cultured Aquatic Species list [26]), only 19 species of crustaceans, 34 species of molluscs, and 36 species of fish have indeed been tested. In the Mediterranean, 24 species are used only in aquaculture, 68 represent wild catch (fisheries), and only two species of bivalves (the oyster *Ostrea edulis* and the clam *Ruditapes decussatus*) contribute to both. For this study, we have focused on the three most studied animal phyla in the field of ocean acidification: crustaceans, echinoderms, and molluscs (for general reviews, see [27–29], respectively). A literature review of 304 articles, published 1 January, 2014, that reported ocean acidification responses for 157 different species (55 crustaceans, 42 echinoderms, and 60 molluscs) only offered limited information on some of the 54 species that are economically important in the Mediterranean Sea (19 crustaceans, one echinoderm, 34 molluscs; Table A1). Information on the direct impact of ocean acidification is available for only 12 harvested species (68 articles) species and 19 harvested species (106 articles) if other species in the same genus are included (Table 1).

Table 1. Harvested species and the number of articles about this species or genus (A = aquaculture, WC = wild catch). Bold species names highlight those with more than three articles.

Harvested Mediterranean species	Fishery type	# Articles on this species	# Articles on this genus	Other studied species of the same genus (# articles)
CRUSTACEANS				
Carcinus aestuarii	WC	0	6	***C. maenas*** **(6)**
Hommarus gammarus	WC	3	1	*H. americanus* (1)
Nephrops norvegicus	WC	2	0	
Palaemon serratus	WC	1	2	*P. californicus* (1), *P. elegans* (1)
Penaeus indicus	A	0	1	*P. plebejus* (1)
Penaeus vannamei	A	0	1	*P. plebejus* (1)
ECHINODERMS				
Paracentrotus lividus	**WC**	**8**	**0**	
MOLLUSCS				
Crassostrea gigas	**A**	**13**	**13**	*C. hongkongensis* (1), ***C. virginica*** **(12)**
Haliotis tuberculata	WC	0	6	*H. coccoradiata* (2), *H. discus* (2), *H. Kamtschatkana* (1), *H. rufescens* (1)
Loligo vulgaris	WC	1	0	
Mytilus edulis	**A**	**14**	**14**	*M. californianus* (2), *M. chilensis* (2), ***M. galloprovincialis*** **(9)**, *M. trossulus* (1)
Mytilus galloprovincialis	**A**	**9**	**19**	*M. californianus* (2), *M. chilensis* (2), ***M. edulis*** **(14)**, *M. trossulus* (1)
Ostrea edulis	A, WC	3	0	
Patella caerula	WC	0	1	*P. vulgata* (1)
Pecten jacobaeus	WC	0	3	*P. maximus* (3)
Ruditapes decussatus	A, WC	3	1	*R. philippinarum* (1)
Ruditapes philippinarum	A	1	3	*R. decussatus* (3)
Sepia elegans	WC	0	10	***S. officinalis*** **(10)**
Sepia officinalis	**WC**	**10**	**0**	

Among those, only five species had available published information in more than 3 articles: 2 species of *Mytilus* mussels, the oyster *Crassostrea gigas*, the squid *Sepia officinalis* and the sea urchin *Paracentrotus lividus*. Negative effects, including delayed growth, increased mortality, and altered physiology, are documented for all these species. However, most of the experiments used for this evaluation are based on short-term perturbation experiments. These fail to address some key modulating factors such as acclimation and evolutionary adaptation [30], ecological interactions, or interaction with other drivers [5]. Hence, it is then likely that laboratory based experiments will both under- and over-estimate the real impact of ocean acidification. Because responses vary greatly among species, we do not make generalizations or employ meta-analyses that are not representative of individual species responses [31,32]. The challenge, then, for evaluating the impacts of ocean acidification on marine resources is to deduce population- and ecosystem-scale responses of organisms that exhibit negative responses to ocean acidification.

Volcanic carbon dioxide vents in the Mediterranean have shown ecological responses to long-term moderate increases in CO_2 levels that retain natural pH variability [33,34]. They are also useful for examining response thresholds and determining which organisms are the most resistant to chronic exposures to elevated CO_2 levels [35]. Communities of organisms exposed to decades of high CO_2 levels provide insights into what to expect in areas that are expected to receive higher-than-average levels of CO_2. There are shortcomings, however, in using volcanic systems as models to indicate how ecosystems will respond to ocean acidification. Although CO_2 vent systems are much larger and longer lasting than the mesocosm and aquarium experiments that have taken place to date, they still only affect relatively small areas of the seabed. Being open systems, their ecology is affected by surrounding areas that have lower CO_2 levels, allowing recruitment and migration of organisms from unaffected habitats [36,37]. Moreover, volcanic vent sites can have highly variable CO_2 levels, with steep gradients in pH and carbonate saturation, so caution is required in using information derived from vent studies in projecting future high-CO_2 scenarios [38]. Thus CO_2 vent systems cannot mimic the effects of global acidification, but they augment predictions based on laboratory and modeling experiments since they show long-term responses of coastal systems to increases in CO_2 levels at a variety of locations worldwide [39].

Only limited information on commercial species is available from the vent studies. For example, none of the fish [33] and only nine invertebrates species listed as commercially important in Table A1 have been studied at Mediterranean CO_2 seeps. The cnidarian *Anemonia sulcata* thrives at high CO_2, and the extra inorganic carbon boosts the photosynthetic productivity of their zooxanthellae [40]. The sea urchin *Paracentrotus lividus* is less resilient to elevated CO_2 than other common shallow-water sea urchins, such as *Arbacia lixula* [41]. Many commercially important molluscs (*Arca noae*, *Astraea rugosa*, *Hexaplex trunculus*, *Mytilus galloprovincialis*, *Octopus vulgaris*, *Ostrea* sp., *Patella caerulea*) disappear from marine communities as CO_2 levels rise along natural gradients off Ischia [33]. Transplantations of adult *Mytilus galloprovincialis* at CO_2 vents show that their periostraca can confer short-term resilience to ocean acidification when exposed to corrosive waters, but that the oligotrophic conditions of the Mediterranean may rob the mussels of sufficient energy to cope with acidification. Conversely, transplantations of the commercially important gastropod *Patella caerulea* showed that they were able to adapt physiologically to acidification, but the shells lacked periostraca and were weakened by the corrosive waters [42].

In both laboratory and field studies, results indicate that numerous commercially important Mediterranean species will respond negatively to ocean acidification. Published studies have focused more heavily on crustaceans, echinoderms, and molluscs, which are more heavily studied phyla also in general (see [27,29,43] respectively, for general reviews). However, insufficient data exist at this time to go beyond simply identifying which commercially important species or genera in the Mediterranean also exhibit negative ocean acidification responses. Studies designed to uncover the mechanisms governing ocean acidification responses may be of great help to close the knowledge gap between harvested Mediterranean species and those at risk from ocean acidification.

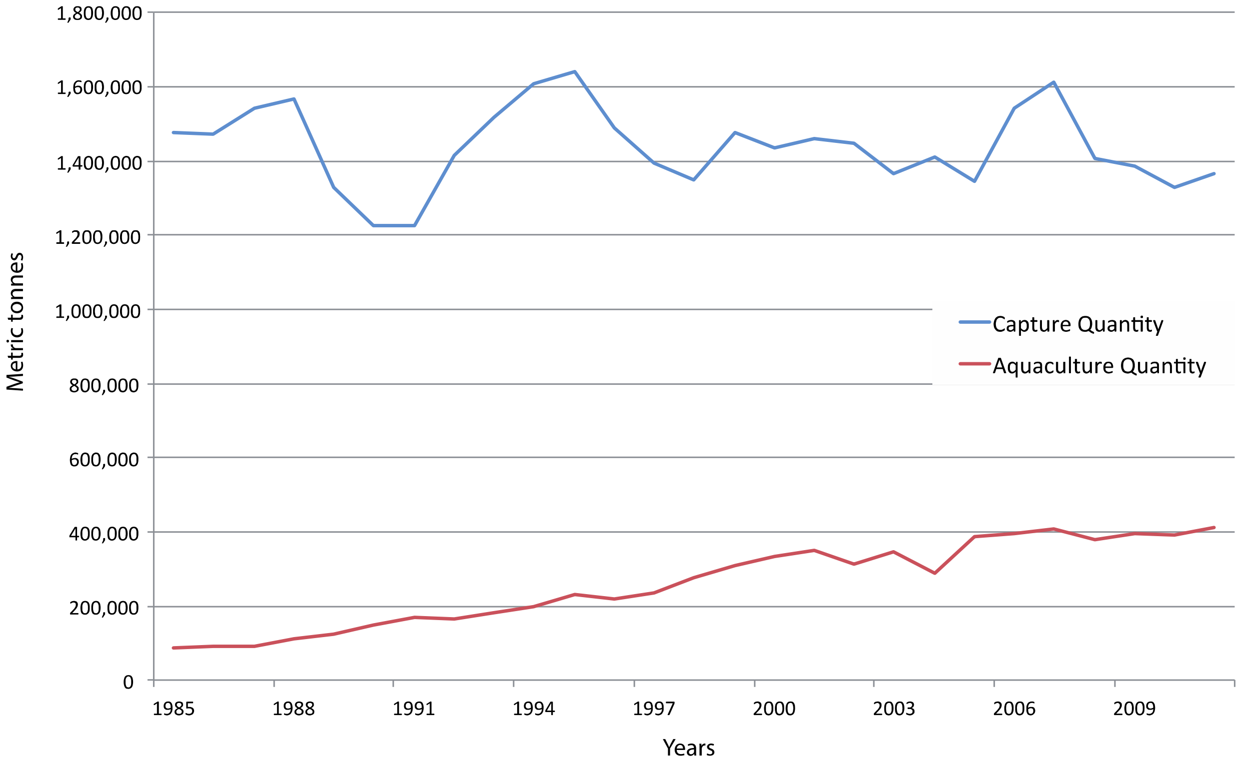
4. Dependence of Mediterranean Countries on Fisheries Harvests

Mediterranean fisheries are locally important in coastal areas where few alternative livelihoods are available, and particularly in less developed Mediterranean nations (Figure 1), where seafood capture can be essential to the subsistence of coastal populations. These factors can be obscured by examining national-scale data, which suggest that the economic importance of commercial fisheries is generally low for most Mediterranean countries relative to their gross national products, and that it makes up just 1% of total world fish production. Nevertheless, fishing and related industries generate employment and revenue [44] for Mediterranean nations.

4.1. Wild vs. *Aquaculture Harvests*

Total fishery production of Mediterranean countries (including both capture fisheries and marine aquaculture) has increased during the last few decades. Disaggregating this production into capture fisheries and aquaculture, however, portrays a slightly different picture. Catches from wild stocks have dropped while aquaculture production has increased substantially. Between 1985 and 2007, aquaculture production across the Mediterranean increased continuously from 87,000 to 415,000 metric tons, equating to a 378% increase in volume (Figure 3). During the same period, capture production decreased from 1.5 to 1.4 million tons (*i.e.*, −8.73%).

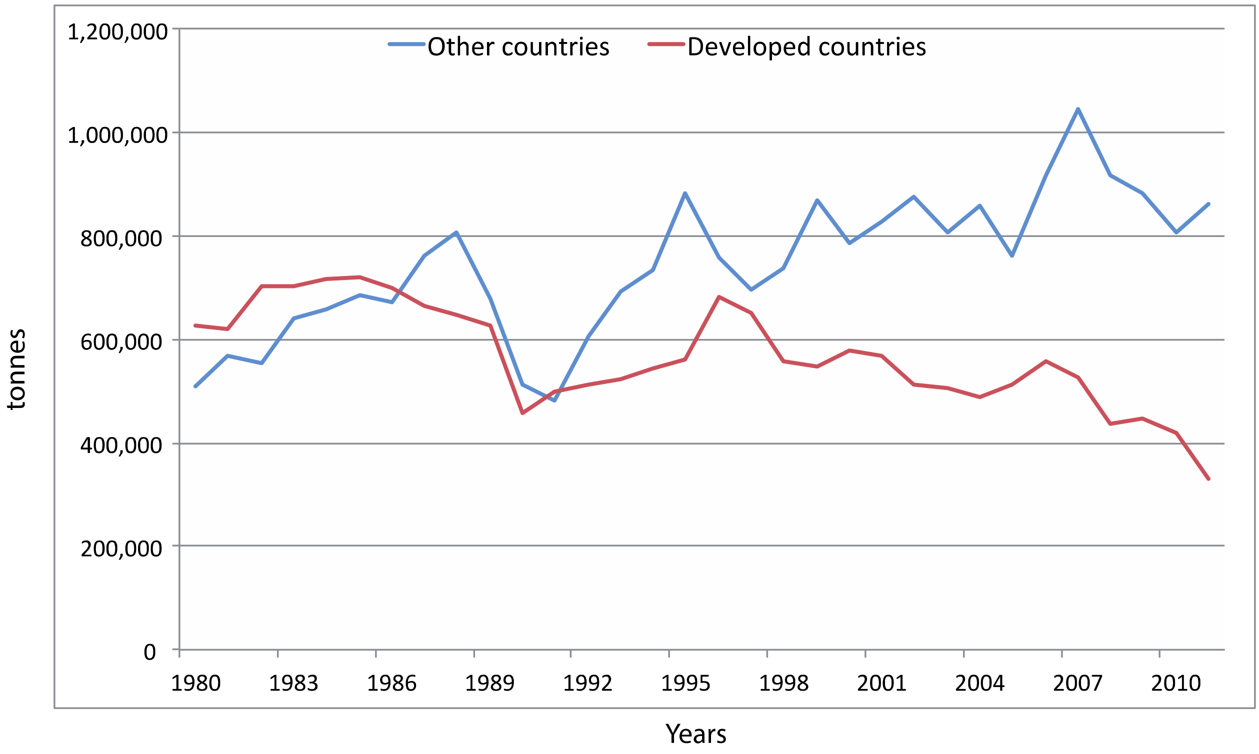
Figure 3. Capture and aquaculture production in the Mediterranean. (source: FAO Fishstat).



In the past two decades, capture production by developed nations (France, Greece, Israel, Italy, Malta, Monaco, Slovenia, and Spain) has fallen below capture production by other nations (Albania, Algeria, Bosnia-Herzegovina, Croatia, Cyprus, Egypt, Lebanon, Libya, Montenegro, Morocco, Palestine, and Turkey) (Figure 3). The EU catch represented approximately 39% of the total Mediterranean catch in 2005, down from 70% during the 1970s [45]. The decrease in wild capture production in developed countries is attributed to limits imposed on fish catch. In contrast, fishing effort and landings have increased among North African and eastern Mediterranean countries with Turkey, Tunisia, Algeria, and Egypt emerging as significant players [46].

In contrast to wild capture production, marine aquaculture in the Mediterranean has quadrupled in the past three decades (Figure 3). While marine aquaculture production has risen steadily in non-developed countries since around 1990, production in developed countries rose continuously from 1980 through to about year 2000, with large year-to-year fluctuations after that (Figure 5). The terms "non-developed" and "others" refer both developing and in-transition economies, as defined by the United Nations. The substantial contribution of non-developed Mediterranean countries to overall fishery production in recent years is due to both large contributions of wild catch and significant expansion of aquaculture capacity (Figures 4 and 5).

Figure 4. Capture production in the Mediterranean (in tons). (source: FAO Fishstat).



Aquaculture in Mediterranean countries focuses largely on the cultivation of molluscs, which dominate production by volume, but finfish production has also steadily increased [47] to make up more than half the monetary value (Table 2). The high value of fish aquaculture is attributed to the fattening of bluefin tuna and the farming of food species used for both other aquaculture species and humans (e.g., sardines and anchovies). Aquaculture is particularly strong in Greece, Italy, and France and growth in this sector can largely be attributed to European Union (EU) incentives for the development of this activity [48].

Figure 5. Marine aquaculture production in the Mediterranean (in tons) (source: FAO).

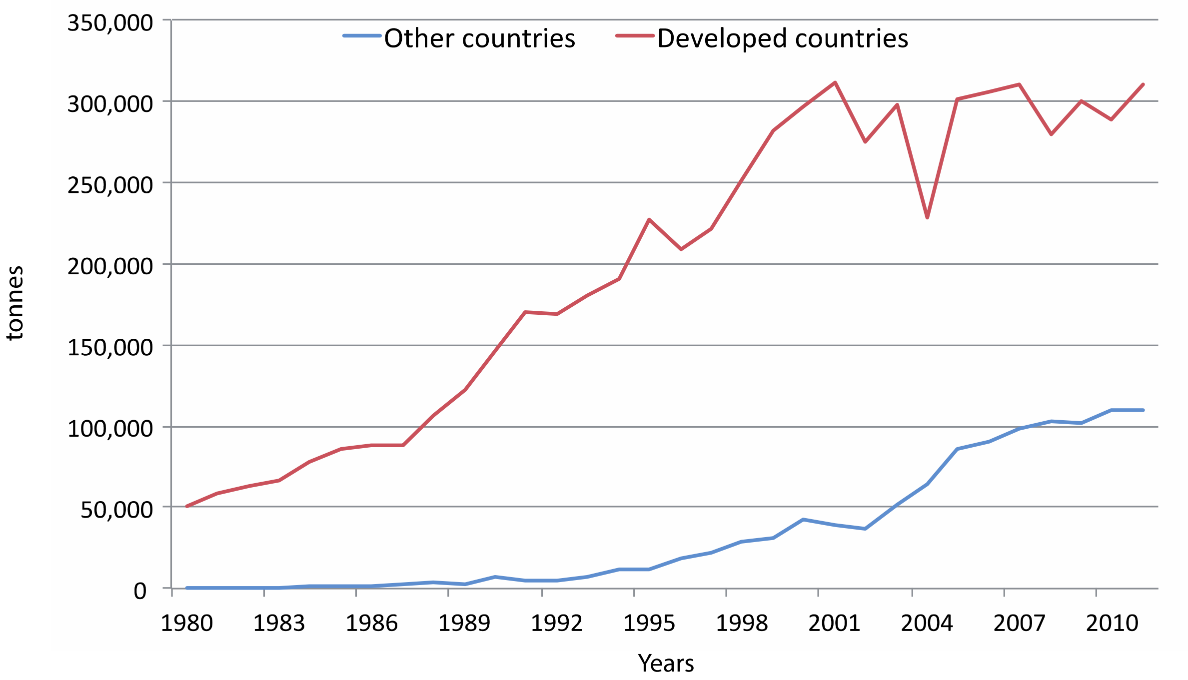


Table 2. Production volume and value of marine aquaculture in Mediterranean countries in 2010 and 2011.

Species	2010		2011	
	Volume (tons)	Value (Thousands of USD)	Volume (tons)	Value (Thousands of USD)
Molluscs	451,909	861,779	474,062	922,807
Fish	249,016	1,526,191	266,559	1,707,428
Other	8,138	32,715	8,662	37,440

4.2. Wild Harvests

Capture fishing activities in the Mediterranean are categorized here as industrial, artisanal or recreational. Within the EU, boats over 12 m in length are considered industrial, while those under 12 m in length (excluding all trawlers) are classified as artisanal, or small-scale [49]. Here, we define recreational fishing broadly and consider it to be any fishing undertaken for non-commercial and non-subsistence purposes.

4.2.1. Industrial and Artisanal Fleets

The industrial fisheries of the Mediterranean are primarily large seiners targeting tuna and swordfish, although hake, sardine, anchovy, and shrimp are also important. These fisheries include fleets from both Mediterranean and non-Mediterranean countries and are backed by major investments from companies and financial groups [50]. Non-Mediterranean nations that fish in the region include Japan, Korea, Russia, Georgia, Ukraine, Bulgaria, and Romania. These industrial fleets focus primarily on a small number of species and operate mainly in deeper waters.

The majority of Mediterranean fishers fall into the small-scale artisanal category, fishing close to shore and targeting multiple species. These fishers come from every Mediterranean country. Anecdotal evidence suggests that more than 80% of Mediterranean fishing vessels are 12 m or less and therefore qualify as artisanal [49,51]. Artisanal fishers can be characterized as owner-operators, working mainly in coastal areas and fishing only a short distance from their home port. They use diverse gear types, operate small boats, and land their catch regularly [50]. Consequently, they are much more dependent on coastal inshore waters, which makes them vulnerable to changes in local ecosystem conditions [49]. To optimize their effort, they use multi-purpose fishing approaches and can change their target fish species throughout the year [52]. Fishing is very important in coastal areas where few other livelihood opportunities are available. Among EU countries, artisanal fishing accounts for 63% of efforts [53]. This seems to be true also for North African and eastern Mediterranean countries [44,54]. Libya, Lebanon, and Syria operate only small fishing fleets that are mostly artisanal and in need of modernization [44].

Detailed information for Turkey provides an example of fleet characteristics in a non-developed Mediterranean nation that is relatively heavily invested in fishing. Most of the fishing in Turkey is small-scale fishing. According to 2012 Turkish Statistical Institute data, there are a total of 14,324 Turkish fishing vessels, 11,845 of which have no radar; 12,896 have no sonar; 9526 have no echo-sounder; 11,707 have no satellite nor GPS connections; and 11,732 have no Rodin sets [55]. The majority of Turkish vessels operate in the Black Sea; out of the 1959 Turkish vessels in the Mediterranean region, most does not have any of technological hardware listed above. In addition, 1787 of the 1959 do not have any refrigeration on board. Of the fish landed on the Mediterranean coast of Turkey, 93.7 percent are sold to wholesalers. Of the 4433 fishery workers in the Mediterranean coast of Turkey, 1757 are fishers themselves, 256 are unpaid household members, and 194 are unpaid [56].

Considering which species are harvested, we find that in 2011 European anchovy (*Engraulis encrasicolus*) and European pilchard (*Sardina pilchardus*) were the two most important finfish species landed in terms of volume for the Mediterranean as a whole (FAO Fishstat data). For EU countries the most important shellfish were the deepwater rose prawn (*Parapenaeus longirostris*), cuttlefish (*Sepia officinalis*), and the common octopus (*Eledone* spp.). Data indicating the value of landings by species are more difficult to access. Within EU countries (minus Greece and Spain) hake (*Merluccius merluccius*), anchovy (*Engraulis encrasicolus*), and deepwater rose shrimp (*Parapenaeus longirostris*) were reported as the most important in terms of value in 2010. Mediterranean fisheries, however, are very diverse and fishers target multiple species. Not one of the species mentioned accounts for more than 8% of the total value of landings [57].

National-scale harvest data makes the picture more complex and indicates that some nations depend much more heavily on species documented to be at risk for ocean acidification [8] than the region does. Sea urchins are a very small portion of Mediterranean Sea production. On the other hand, mussel production is about 14% of the total production in Italy, 11% in Greece, and nearly 24% in France. Oyster production mainly occurs in France and represents 13% of its total production in the Mediterranean Sea (Table 3).

No information is currently available on the effect of ocean acidification on the most heavily harvested species. In addition, much of the catch data are not described at the species level, and are instead generally described (e.g., marine fish or natantian decapods not elsewhere identified). For example, 43% of the Mediterranean catch by volume falls into the "natantian decapod not elsewhere identified" category that accounts for approximately 3000 different shrimp species. Confounding assessment of ocean acidification's possible impacts on Mediterranean fishery harvests is our understanding that each of these species may respond to ocean acidification in different ways. It is possible, however, to conclude that of the wide range of species harvested, several are likely to experience negative impacts from ocean acidification. However, the diversity of harvests helps decrease exposure of Mediterranean nations to ocean acidification: because no single at-risk species or group of species bring the major economic benefit to Mediterranean nations, there are no dependent nations or regions that are positioned to suffer acute harm from ocean acidification if that single species fishery should suffer.

Table 3. Production in the Mediterranean Sea for mussels, oysters and urchins. (2007, metric tons, source: FAO).

Species	Croatia	Bosnia and Her.	Italy	Greece	Mor.	Slov.	Tunisia	Turkey	Albania	Algeria	Spain	Egypt	France
Sea urchins											**3**		
Oysters	555	20	10	141			10	31			<0.5		**8,800**
Mussels	3,013	50	**58,479**	**22,653**		301	696	2,666	1360	44	<0.5		**16,060**

4.2.2. Recreational Fisheries

Recreational fishing is a popular and growing activity in the Mediterranean among both tourists and local people, for whom it forms an important part of coastal culture. As a largely unregulated and unstudied activity in the Mediterranean, few data are available for number of recreational fishers, their catch volume, and total expenditure [58,59]. The economic value of recreational fisheries, however, is thought to be high. Estimates of annual expenditure in Europe as a whole are 25 billion € annually [60], with anglers alone contributing 8–10 billion €. Isolated case studies indicate the local importance of recreational fisheries. For example, the annual expenditure by marine recreational fishers across France is estimated to range from 1200 to 2000 million euros [59] but we have no indication of what proportion is from the Mediterranean. Recreational fishers in the Cap de Creus MPA were reported as spending 500€ annually per person, primarily in the village adjacent to the MPA [61]. Without the number of people engaged in this activity, it becomes difficult to estimate total expenditure. In Mallorca 5.2% of the population (37,265 people) is reported to participate in recreational fishing annually [62] but estimates on the average spending of each fisher is lacking so the total economic impact is unclear.

Target species vary considerably by location, especially for shore-based activities; however, there is some commonality among species for anglers fishing from boats. Species of common interest include game species (such as blue shark, tunas, marlin, and swordfish; [63]), most of which are top predators and not directly affected by ocean acidification. Given current knowledge on biological sensitivity it is very difficult to assess the impact of ocean acidification on these species and thereby on recreational fisheries as such. However, as mentioned previously, ocean acidification may operate indirectly by disrupting food webs or altering physical habitat.

Because of the heterogeneous nature of Mediterranean fishing fleets, their ubiquity across the Sea, and the diversity of species they target, it is difficult to fully characterize them. Furthermore, under-reporting of Mediterranean landings is likely; landings by recreational fishers go largely unrecorded but are substantial. Morales-Nin *et al.* [62] estimate that Mallorcan recreational fishers catch approximately 1209 tons annually, but the catch by visiting recreational fishers is unknown. The study of French recreational fishers found that low-intensity shellfish gathering was the most common activity; harvests like this are very difficult to quantify. In contrast, angling (both on shore and from boats) accounted for 24,500 tons of fish caught annually [59]. The estimated catch by recreational fishers in Italy in 1994 was about 24,000 tons compared to 237,000 tons by commercial fishers [60]. Official statistics should, therefore, be considered indicative rather than absolute [50]. It is safe to conclude, however, that recreational fishing provides a significant economic benefit to coastal areas around the Mediterranean. It is probable that the recreational activity is concentrated in wealthier, likely developed, nations, where these activities could be substituted for other coastal activities in the event of declining fisheries from ocean acidification.

4.2.3. Employment

Within the EU direct employment in fisheries has decreased over the last decade, while it has tended to increase within the North African countries. In 2005, it was estimated that approximately 720,000 fishermen worked in Mediterranean waters. Of these, 90,000 were from the EU and 150,000 were from North Africa, while the remaining 120,000 were from other countries [45]. Employment data for fisheries and their associated industries (processing, distribution, *etc.*) are available for most Mediterranean countries (Table 4), although for some countries it is not clear what proportion of fishers are active in the Mediterranean (e.g., France and Spain also have fleets in the Atlantic, Turkey has a large Black Sea fishing fleet, and Egyptian fishers also operate in the Red Sea).

Table 4. Employment in fisheries. Numbers in italics are estimates. Asterisk indicates that it is not clear what proportion of these fishers operate in the Mediterranean. ([1] [46]; [2] [45]; [3] [64]; [4] [54] ;).

Country	Employment—Capture Fisheries		
	Primary (No. Fishers)	Secondary (No. Employed in Processing, Distribution, etc.)	Year of Data Collection
Albania [1]	2,400	ND	ND
Algeria [1]	28,225	84,675	2000
Bosnia	ND	ND	ND
Croatia [1]	20,000	ND	2006
Cyprus [2]	1,350	ND	2005
Egypt *[1]	600,400	ND	2000
France *[2]	19,624	ND	2008
Greece [3]	29,313	ND	2008
Israel [1]	1,503	2,300	2005
Italy [3]	29,562	ND	2008
Lebanon [4]	4,000	ND	Unclear
Libya [1]	11,500	3,500	2003
Malta [2]	2,100	ND	2005
Monaco	ND	ND	ND

Table 4. *Cont.*

Country	**Employment—Capture Fisheries**		
	Primary (no. Fishers)	**Secondary (no. Employed in Processing, Distribution, *etc.*)**	**Year of Data Collection**
Montenegro	ND	ND	ND
Morocco *[1]	70,000	40,000	2005
Palestine	ND	ND	ND
Slovenia [2]	343	ND	2005
Spain *[3]	30,958	ND	2008
Syria [1]	13,252	7550	2005
Tunisia [1]	53,000	47,000	2003
Turkey *[3]	53,893	ND	2008

When comparing primary (fishing) to secondary (processing and distribution) employment, the picture is unclear. In Algeria the ratio of secondary to primary employment is 3:1, while it is 1.5:1 in Israel. For other countries in North Africa the number of secondary employees is always below the number of primary employees (Libya, Morocco, Syria, and Tunisia).

In total, employment in capture fisheries and aquaculture for all Mediterranean countries represents a very small part of the primary sector. At the individual country level, a more heterogeneous picture emerges. Among less developed countries, fishing and its associated industries provide a greater contribution to GDP and support higher levels of employment. Employment in related industries and services indicates a wider social significance of the fishing industry [65]. Estimates suggest that for each person employed in capture or aquaculture activities, four jobs are created in secondary activities [44].

4.3. Consumption and Trade of Seafood

Consumption of fish and other seafood varies greatly between countries. Annual per capita seafood consumption can be calculated for each Mediterranean country from FAO data (Table 5). This groups together consumption of crustaceans, fish body oil, fish liver oil, demersal fish, pelagic fish, other marine fish, and other aquatic animals.

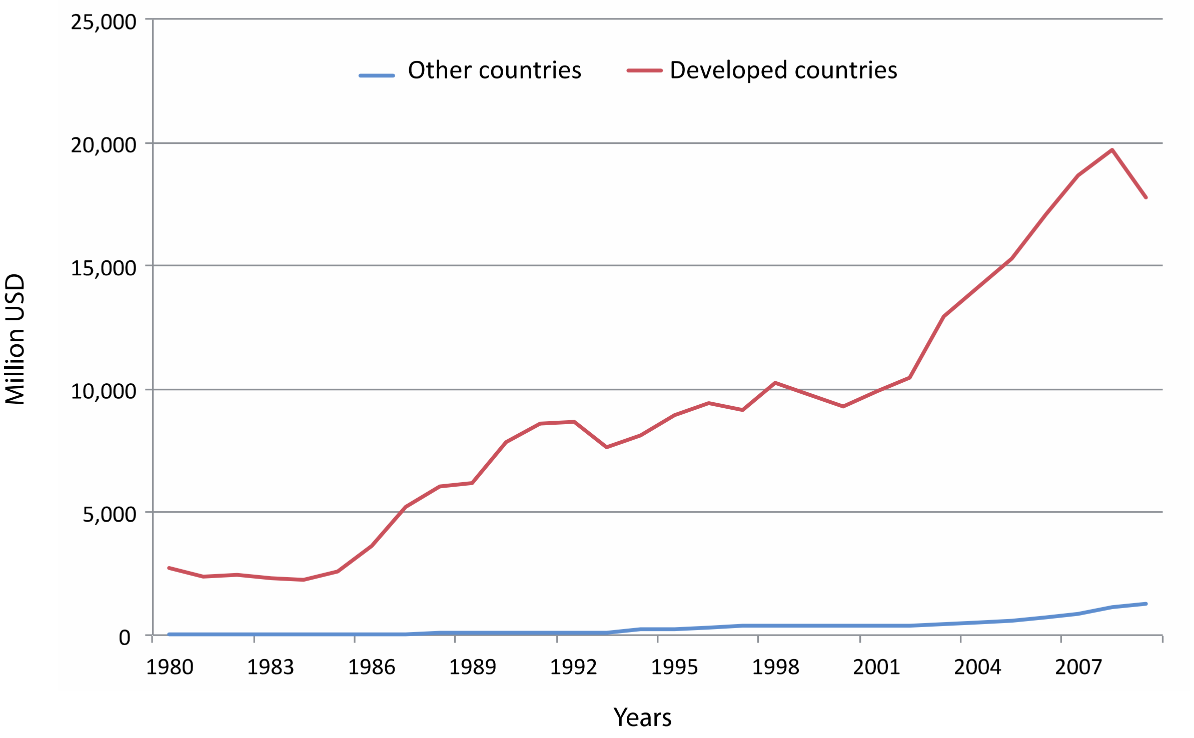
Table 5. Fish consumption by country (source: [66]).

Developed Countries	**kg/cap/y**	**Developing Countries**	**kg/cap/y**
Albania	3.4	Algeria	4.5
Bosnia Herzegovina	4.2	Cyprus	10.1
Croatia	10.3	Egypt	5.1
France	20	Lebanon	8
Greece	8.6	Libya	5.9
Israel	4.8	Morocco	9.4
Italy	12.5	Syria	2.2
Malta	24.9	Tunisia	8.9
Montenegro	2.5	Turkey	5.5
Slovenia	5.1		
Spain	20.2		

In developed Mediterranean countries, average seafood consumption is roughly 10.6 kg per capita per year. However, variation is large, with three countries consuming at least 20 kg per year per capita. In contrast, average seafood consumption in the developing Mediterranean countries is much less at around 6.6 kg per capita per year. Fish consumption has been growing across the Mediterranean. Between 1961 and 2005, consumption increased by 87% within EU Mediterranean countries and by 216% within North African and Middle Eastern countries. This was largely driven by population and income growth. Total consumption is also forecast to grow to 2030 with predicted growth strongest in North African and Middle Eastern countries, again due to population growth [66].

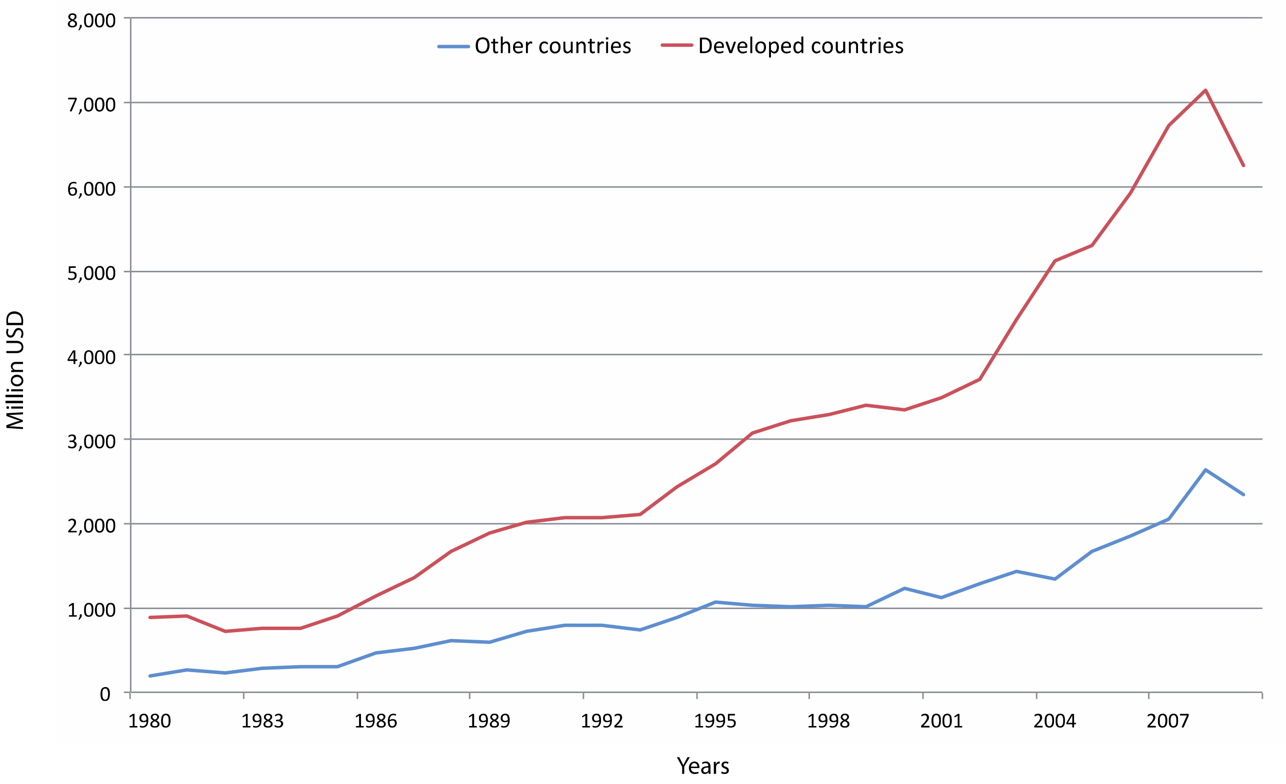
To respond to the growing demand for seafood despite the decline in capture fisheries and limited aquaculture production across the Mediterranean, developed countries in the region (France, Italy, Spain, Greece) have turned to imports. Developed Mediterranean countries currently import significantly more seafood than developing countries (Figure 6). Imports have been growing in all countries, although imports by less developed countries typically focus on species of lower commercial value [66]. These increases can largely be attributed to population growth, increased urbanization and increased wealth, rather than recent trade agreements between Mediterranean countries [66].

Figure 6. Imports (in million USD). (source: [46]).



Fisheries exports are increasing regionally as well (Figure 7). Developed countries export mainly fresh fish, while less developed countries focus more on prepared and preserved fish products (including higher value crustaceans and molluscs). This difference of products exported by developed and non-developed countries is due largely to strict import food quality and safety requirements of receiving (often developed) countries, which many poorer nations cannot maintain for fresh products. Such structural and institutional barriers mean that many of the less developed Mediterranean countries cannot take full advantage of their duty-free access to the EU market for many of their fisheries products and broaden exported offerings. Egypt's situation clearly demonstrates this. It is one of the largest producers of fish in the Mediterranean, but 99.5% of their production goes to the domestic market [66].

Figure 7. Exports (in millions USD) (source: [46]).



5. Discussion

This review has uncovered significant data gaps in both social and ecological knowledge that make it challenging to assess the risks that Mediterranean nations face from ocean acidification. However, we can use the data that is available to make a preliminary assessment of the relative exposure of Mediterranean nations to this threat. By exploring the characteristics of acidification, species harvested, fishery makeup, and economic benefits from Mediterranean fishing, we can identify trends and gaps that can direct future research efforts.

Given that the entire Mediterranean is likely to undergo relatively uniform acidification from the absorption of atmospheric carbon dioxide, local processes, such as nutrient overloading and hydrological and groundwater changes [67], will likely cause the majority of regional variation in the Mediterranean's acidification signal. From an oceanographic perspective, the exposure of Mediterranean fisheries assets to ocean acidification that is caused only by atmospheric CO_2 (sometimes called "anthropogenic ocean acidification" [16]) appears fairly uniform at this time; however, the development of basin-scale physical-biogeochemical models may add more detail to this conclusion.

When we consider the ocean acidification response of economically relevant Mediterranean species, we are faced with another set of gaps. Knowledge is growing rapidly about the response of organisms to ocean acidification, but our understanding of the responses of economically relevant species lags far behind. Generally, bivalve shellfish fare worse [8] under ocean acidification than other taxa, suggesting that if this trend also holds for most Mediterranean harvested species, artisanal and recreational fishers who target these groups may be more exposed to ocean acidification's effects. Furthermore, different exposure arises among countries depending on the blend of species harvested. For example, the two largest Mediterranean fishery producers, including both wild catch and aquaculture, are Turkey and Italy. Both nations' production is primarily based on herrings, sardines, anchovies, while Italian fishers also target mussels, clams, cockles, and ark shells.

The lack of disaggregated catch data (volume and value) by boat size or gear type makes it difficult to examine specifically how ocean acidification may impact these different fishing sectors. Generally, industrial fishers are more insulated from shifts in natural resources that may follow from environmental changes than artisanal fishers are. This is partly due to the industrial fleets' greater ability to increase fishing effort to pursue elusive harvests and partly to their ability to divest from failing fisheries caused by environmental change. Of course, employees of industrial fleets may not have such clear-cut alternatives if the fishery declines, but they may be more able to find work elsewhere (either within a fishery industry or outside of it) compared to artisanal fishers given their lower economic exposure within the fishery. Compared to industrial fleets, artisanal fishers such as those profiled in Turkey have minimal technology available to help them increase fishing efforts. As owner-operators, their capital is heavily invested in region- or species-specific gear, decreasing their ability to adapt to changing environmental conditions. They do tend to harvest a range of species, somewhat insulating them from biogeographic shifts of one target species that follow from environmental change, but if overall ecosystem productivity and species diversity decline from ocean acidification, their harvests could decline as well. Although the economic revenues from artisanal fishing may not be significant, this sector is most exposed from possible impacts of ocean acidification given the small economic margins available from fishing and the significant capital costs associated with any change, not to mention the possible barriers in place regionally from lack of other employment alternatives. As the fishing fleets in non-developed nations, particularly around the southern Mediterranean, are largely artisanal and growing rapidly, yet in need of modernization, they seem to be most exposed from ocean acidification.

Aquaculture operations that raise shellfish may in fact be less exposed than artisanal or recreational fishers who gather shellfish from the wild. Shellfish hatcheries tend to be larger-scale, having more in common with industrial fishery fleets, and can proactively work to avoid harm to production by installing monitoring equipment, as has happened in some United States oyster hatcheries [68]. Recreational fishers tend to be relatively less exposed than either group since they do not seek to subsist only on the proceeds of their labor the way artisanal fishers or small business owners of aquaculture operations often do.

Nations with large employment ratios of processors to fishers may be relatively more exposed to ocean acidification as well. When larger numbers of coastal residents depend on work and income generated by a single marine resource, the consequences to the human community if the resource declined would be much larger than in communities where diverse employment opportunities exist [15].

Another factor that increases exposure of individual Mediterranean nations to ocean acidification is consumption of seafood [69]. Without having dietary data divided up by taxon, without more information on the relationship between artisanal fishing and dietary dependence, and without conclusive information about the responses of harvested species, we can only estimate exposure by assuming that nations with higher seafood consumption are more exposed to ocean acidification. Developing nations presumably have lower access to high quality protein, and may more depend nutritionally on seafood [69]. A positive outcome of the trade barriers mentioned above may be that these nations' seafood supply goes to domestic markets (as in the case of Egypt) and offer this nutritional benefit locally, rather than satisfying appetites abroad, which can pay a higher price for the luxury. On the whole, the Mediterranean countries consume more seafood than they produce, so they are likely to be more exposed to ocean acidification than if income from fishing were the only benefit.

Future work to explore the impact of ocean acidification on Mediterranean nations could involve computable general equilibrium models (CGE models) for multi-sectors and multi-countries [70]. These models require a system of equations to assess the added impact of ocean acidification on linkages across sectors. This would be possible if a good-fitting CGE model existed to which environmental impacts could be added to assess the marginal impact and trickle-down effect of ocean acidification over sectors. From another dimension, it would be ideal to be able to assess the impact of ocean acidification on any chosen economic output variable (such as employment in fisheries, trade, protein intake of households, *etc.*) in the region and in a country by conducting data-based sensitivity analysis. Given that most relationships in nature are non-linear, we suggest usage of nonlinear sensitivity models, which suggest that there is not a direct, linear and constant relationship between ocean acidification (input) and economic output variables. Assuming nonlinear sensitivity calls for potentially measuring it with a variance-based sensitivity analysis within a probability frame, where one can decompose the variance of the system output (a chosen economic variable such as the examples above) into percentages caused by several input variables, which include ocean acidification. As an example, if one had data on ocean acidification, agricultural runoff (pollution, *etc.*) as input variables in a region, one could measure the sensitivity of the output variable (such as employment in fisheries) to ocean acidification. If, in this hypothetical case, 80% of the protein intake variance was caused by variance in agricultural runoff, 22% by variance in ocean acidification and 8% by interactions between ocean acidification and pollution, these percentages would be measures of sensitivity across the whole input set, because they are nonlinear responses with interactions in non-additive systems and models. Completing estimates of this sort will require coordinated efforts in data collection of same variables across countries and across time.

6. Conclusions

Richer, developed countries can more easily adapt to risks than poorer, non-developed countries [69,71]. In the Mediterranean, non-developed countries have been increasing both wild and aquaculture fishery production dramatically, which provides both needed income but also exposes them more to ocean acidification due to their rapid industrialization. These fishermen generally lack advanced technology and include many owner-operators, which enhances their exposure even more. Trade barriers hinder the export of fresh products from developing nations, which encourages domestic consumption. Although this provides households with high quality food, it also increases dependence of people in developing nations on marine resources. Taken together, the factors reviewed in this paper suggest that non-developed Mediterranean nations that are greatly increasing their fishery production via both wild and aquaculture investments, that have a large ratio of processors/distributors to fishermen, bivalve shellfish as a strong part of their aquaculture industry, and large numbers of artisanal fishers and harvesters, are the most exposed to risks resulting from ocean acidification. Nations along the southern Mediterranean tend to fit more of these characteristics than others.

This study must be considered only a first step at assessing elements of the risk that Mediterranean nations face from ocean acidification. A more formal risk assessment [16] would require the collection of much more data to evaluate the development of ocean acidification in the Mediterranean, at a more detailed level than the equilibrium calculations we have done to assess the ocean acidification response of fishery-targeted species in the region, to gather more detailed harvest data at a species-resolving scale and to understand the interaction of export, domestic, subsistence, and industrial markets in distributing marine harvests from the Mediterranean. It is extremely likely that the risk profile of each Mediterranean nation will differ from its neighbors, as a result of the different factors mentioned above and other external socioeconomic factors, such as the developed/non-developed status of nations' economies and each nation's social resilience. This study underscores the need for marine scientists, fisheries economists, and other social scientists to work together to improve our capacity to project future environmental and economic consequences from ocean acidification. To assess possible impacts on humans, it is also critical to lead more studies focused on the species and ecosystems having the most economic importance.

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Author Contributions

Except for the first and last authors, who managed the draft of the paper, all authors are listed by alphabetical order because they participated equally in writing the manuscript.

Appendix

Table A1. List of animal species used in aquaculture or in fisheries in the Mediterranean.

Phylum	Species Name	Aquaculture	Fishery
Cnidarians	*Anemonia sulcata (=A. viridis)*		x
	Corallium rubrum		x
Crustaceans	*Aristeus antennatus*		x
	Carcinus aestuarii		x
	Dromia personata		x
	Eriphia verrucosa		x
	Hommarus gammarus		x
	Liocarcinus corrugatus		x
	Maja crispata		x
	Maja squinado		x
	Nephrops norvegicus		x
	Palaemon serratus		x
	Palinurus elephas		x
	Palinurus mauritanicus		x
	Parapenaeus longirostris		x
	Paromola cuvieri		x
	Penaeus indicus	x	
	Penaeus vannamei	x	
	Scyllarides lattus		x
	Scyllarus arctus		x
	Squilla mantis		x
Echinoderms	*Paracentrotus lividus*		x
Fish	*Acipenser baerii*	x	
	Argyrosomus regius	x	
	Boops boops		x
	Conger conger		x
	Dentex dentex	x	
	Dicentrarchus labrax	x	
	Engraulis encrasicolus		x
	Lophius piscatorius		x
	Merluccius merluccius		x
	Mricomesistius poutassou		x
	Mugil cephalus	x	
	Mugilidae sp.	x	
	Mullus barbatus		x
	Mullus surmuletus		x
	Oncorhyncus mykiss	x	
	Pagellus bogaraveo	x	
	Pagellus erythrinus	x	
	Pagrus major	x	
	Pagrus pagrus	x	
	Phycis blennioides		x
	Pristirius melanostomus		x
	Psetta maxima	x	
	Puntazzo puntazzo	x	
	Sardina pilchardus		x

Table A1. *Cont.*

Phylum	Species Name	Aquaculture	Fishery
Fish	*Sardinella aurita*		x
	Sciaenops ocellatus	x	
	Scomber scombrus		x
	Scophthalmus maeoticus	x	
	Siganus rivulatus	x	
	Sparus aurata	x	
	Spicara maena		x
	Spicara smaris		x
	Trachurus trachurus		x
	Trachyrhynchus trachyrhynchus		x
	Trisopterus minutus		x
	Umbrina cirrosa	x	
Molluscs	*Aequipecten opercularis*		x
	Alloteuthis media		x
	Arca noae		x
	Astrae rugosa		x
	Bolinus brandaris		x
	Buccinulum corneum		x
	Cardium edule		x
	Ceratoderma glaucum		x
	Cerithium vulgatum		x
	Crassostrea gigas	x	
	Donax semistriatus		x
	Eledone cirrhosa		x
	Eledone moschata		x
	Ensis siliqua		x
	Glycimeris bimaculata		x
	Haliotis tuberculata		x
	Hexaplex trunculus		x
	Loligo vulgaris		x
	Monodonta articulata		x
	Mytilus edulis	x	
	Mytilus galloprovincialis	x	
	Naverita josephina		x
	Octopus vulgaris		x
	Ostrea edulis	x	x
	Patella caerulea		x
	Pecten jacobaeus		x
	Rossia macrosoma		x
	Ruditapes decussatus	x	x
	Ruditapes philippinarum	x	
	Sepia elegans		x
	Sepia officinalis		x
	Tadarodes sagittatus		x
	Venerupis aurea		x
	Venus verrucosa		x
Tunicates	*Microcosmus sulcatus*		x
	Microcosmus sabatieri		x

Conflicts of Interest

The authors declare no conflict of interest.

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