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Impact of climate change in Mediterranean aquaculture

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Abstract

The Mediterranean Sea is the biggest marginal sea of the Earth and is at the centre of the life for several millions of people. Seafood is consumed widely in this region, with an average of 16.5 kg/capita/year, and one-fourth of the seafood supply comes from aquaculture activities. The Mediterranean aquaculture sector has expanded in recent decades. Production increased by 77% over the past decade reaching about 1.3 million metric tonnes in 2009. The total value of production was around 3700 million US dollars, representing 3.4% of the value of global aquaculture production. The growth of seafood demand in the Mediterranean is expected to increase in the future, especially in southern countries. Yet, during the 21st century, the Mediterranean basin is expected to observe: (i) an increase in air temperature of between 2.2°C and 5.1°C; (ii) a decrease in rainfall of between 4% and 27%; (iii) an increase in drought periods related to a high frequency of days during which the temperature would exceed 30°C; and (iv) an increase of the sea level of around 35 cm and saline intrusion. Moreover, extreme events, such as heat waves, droughts or floods, are likely to be more frequent and violent. This paper reviews the present status of Mediterranean aquaculture (e.g. production trends, main farmed species, production systems, major producing countries), the most relevant impacts of climate change on this sector (temperature, eutrophication, harmful algae blooms, water stress, sea level rise, acidification and diseases) and proposes a wide range of adaptation and mitigation strategies that might be implemented to minimize impacts.

Key words: adaptation, aquaculture, climate change, Mediterranean Sea, mitigation.

Introduction

The semi-enclosed Mediterranean Sea is the biggest marginal sea on Earth, representing 0.69% of the global ocean surface and 0.27% of the global ocean volume. It has a surface area of 2.5 million km^2 and a total water body of about 4 million km^3 (Goudie 2001). The Mediterranean Sea is one of the most oligotrophic seas in the world (UNEP 1989), with some of the largest rivers of Europe and Africa draining the nutrient- and sediment-rich waters directly or indirectly into it. The basin is directly linked to the Atlantic Ocean through the Strait of Gibraltar, and the entire body of water is renewed every 100 years. Located between the mid-latitude storm rainband and the Sahara Desert, it experiences a profound seasonal cycle (Peixoto *et al.* 1982). The hydrological cycle is especially sensitive to the timing and location of the winter storms as they move into the region. Interannual climate variability is closely related to variability in the Atlantic sector such as the North Atlantic Oscillation (NAO) (Hurrell 1995, 1996; Rodo *et al.* 1997; Eshel & Farrel 2000).

The Mediterranean basin displays a great variety of climatic, physical, ecological, social, economic and cultural traits, and despite the apparent diversity, the Mediterranean region has long been recognized as a single functional climatic, ecological, economic and social system. The basin is characterized by a generally mild climate, winter-dominated rainfall, dry summers, with a profusion of microclimates, ranging from the hot dry conditions of the Nile delta to the cooler and somewhat wetter conditions of the Ebro region. Despite the differences in microclimate, all areas are characterized by warm or hot dry summers and wetter cooler winters, and the influence of the sea that reduces daily and seasonal temperature extremes and results in diurnal land–ocean breezes (Jeftic *et al.* 1996). Yet, the prospect of major climate change is a source of growing concern, raising serious questions over the sustainability of the region.

Aquaculture in Mediterranean Sea

Production trends

In 2009, the total world seafood production reached 162 million tonnes, representing a 19% increase in production over the past decade (Fig. 1). This was entirely due to the 84% increase in aquaculture production, since capture fisheries declined in the same period by 3% (1999–2009). The technology applied has evolved rapidly as a result of the modifications of existing farming facilities and the development of new farming concepts, e.g. offshore submerged netcage technology. As a consequence, presently, a wide range of production activities of marine species co-exist in different Mediterranean environments using a variety of technologies, from extensive mollusc or fish production to highly intensive raceways or netcage fish farming.

Mediterranean aquaculture production has increased by 77% over the past decade, especially in the brackish environment (Fig. 2), reaching about 1.3 million tonnes in 2009. Yet, it only represented 1.8% of the world's total production. The value of Mediterranean aquaculture ranged around 3.700 million US dollars in 2009 (Fig. 3), representing 3.4% of the global aquaculture value. The Mediterranean aquaculture has grown steadily over the

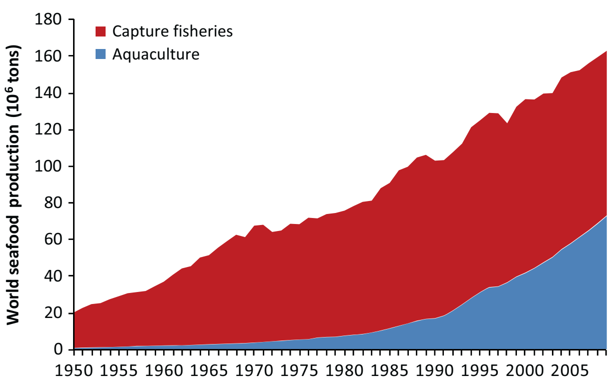

Figure 1 Evolution of world capture fisheries and aquaculture production (million tonnes) between 1950 and 2009 (*source*: FAO Fishstat).

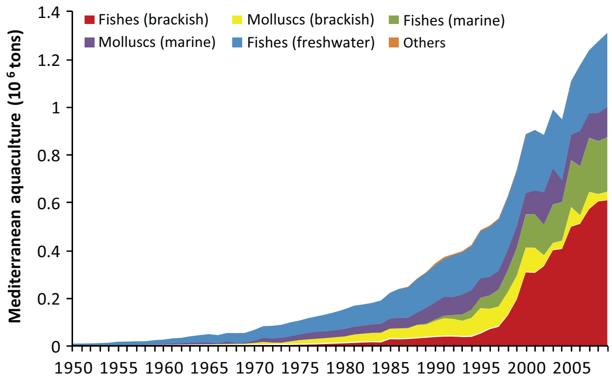

Figure 2 Evolution of Mediterranean aquaculture production (million tonnes), in brackish, marine and freshwater systems, between 1950 and 2009 (*source*: FAO Fishstat).

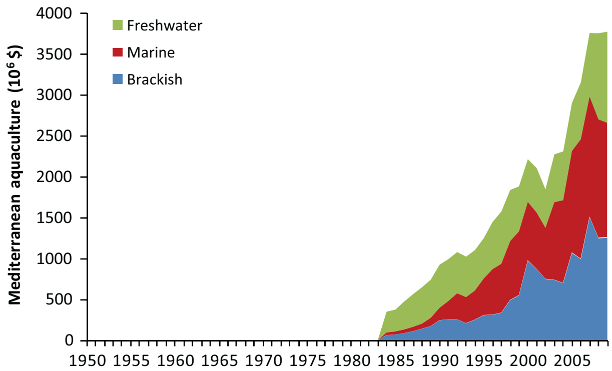

Figure 3 Evolution of total Mediterranean aquaculture production (in US dollars) between 1950 and 2009 (*source*: FAO Fishstat).

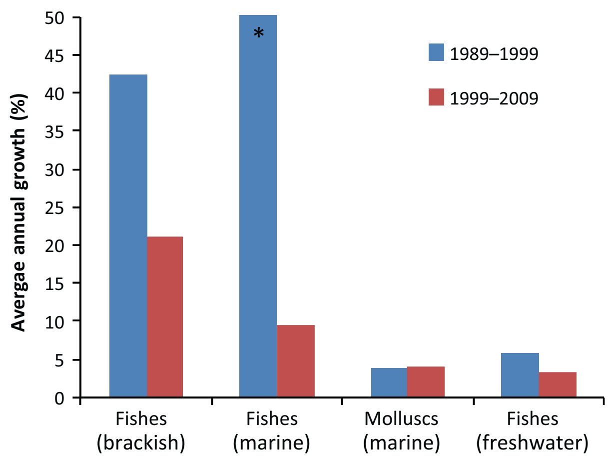

Figure 4 Average annual growth (% of increase) of the major FAOStat groups, between 1989 and 1999, and 1999 and 2009, in the Mediterranean Sea (*source*: FAO Fishstat). *Out of scale, representing a 367% increase.

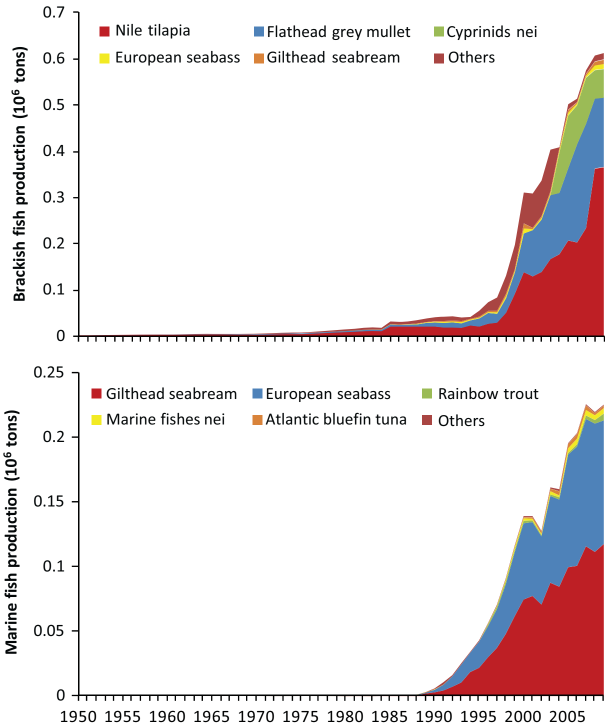

Figure 5 Evolution of total Mediterranean aquaculture fish production (million tonnes), in brackish and marine systems, between 1950 and 2009 (*source*: FAO Fishstat).

past two decades (Fig. 2), but with lower annual growth rates for marine and brackish fish production in the past decade (1999–2009, Fig. 4). The fish species that have contributed most to these high growth rates are the Nile tilapia (*Oreochromis niloticus*) and the flathead grey mullet (*Mugil cephalus)* in brackish systems (Fig. 5), and the gilthead seabream (*Sparus aurata*) and European seabass (*Dicentrarchus labrax*) in marine systems (Fig. 5). The rapid increase in the production of these marine carnivorous fish is quite striking and results from the development of reliable seed production techniques, the formulation of specialized feeds and the application of intensive production systems, particularly cages. Furthermore, the support from the EU and strong markets from the late 1980s and early 1990s have also played a significant role.

Current production status: main species and producing countries

In 2009, marine aquaculture production attained 355 306 tonnes, representing 27% of the total Mediterranean production. The gilthead seabream (*Sparus aurata*) was the most important resource reaching over 118 000 tonnes (i.e. 33%), the European seabass (*Dicentrarchus labrax*) over 95 000 tonnes (27%), followed by the Atlantic bluefin tuna (*Thunnus thynnus*) with only 1994 tonnes (~0.6%) and meager (*Argyrosomus regius*) with 1775 tonnes (0.5%) (upper panel in Fig. 6). Nonetheless, the second most important marine resource (in quantity) was the Mediterranean mussel (*Mytilus galloprovincialis*) attaining over 115 000 tonnes (32%), and the fourth was the Pacific cupped oyster (*Crassostrea gigas*), with about 6900 tonnes (1.9%) (Fig. 6).

Brackish aquaculture production in the Mediterranean Sea in 2009 reached 645 747 tonnes (49% of the total production), with the Nile tilapia (*Oreochromis niloticus*) reaching ~366 000 tonnes (57%), the flathead grey mullet (*Mugil cephalus)* ~150 000 tonnes (23%), the cyprinids ~62 000 tonnes (9.6%) and the Japanese carpet shell (*Ruditapes philippinarum*) around 31 600 tonnes (5%). Representing <2% of the total brackish production, there were the torpedo-shaped catfishes (*Clarias* spp.), gilthead seabream, European seabass, Mediterranean mussel and meagre (middle panel in Fig. 6).

Last, freshwater production represented 24% of the total production (312 673 tonnes) in 2009. The main freshwater species produced were the rainbow trout (*Oncorhynchus mykiss*) with ~169 000 tonnes (54%), followed by the flathead grey mullet (~62 460 tonnes, 20%), common carp (*Cyprinus carpio*, 25 605 tonnes, 8.2%), Nile tilapia (~24 460 tonnes, 7.8%), torpedo-shaped catfishes (9000 tonnes, 7.8%) and other tilapias (~7843 tonnes, 2.5%). Representing <0.6% of the total freshwater production, were brown trout (*Salmo trutta*), roach (*Rutilus rutilus*) and European eel (*Anguilla anguilla*) (lower panel in Fig. 6).

The major Mediterranean producing countries in 2009 were: Egypt (~0.7 million tonnes; ~1240 million dollars), Italy (~0.16 million tonnes; ~660 million dollars), Turkey (~0.16 million tonnes; ~615 million dollars), Greece (~0.12 million tonnes; ~550 million dollars), France (~0.06 million tonnes; ~260 million dollars), Spain (~0.05 million tonnes; ~230 million dollars) and Israel (~0.02 million tonnes; ~70 million dollars). Production from all the other Mediterranean countries ranged between 13 000 tonnes (~55 million dollars, Croatia) and 240 tonnes (~1 million dollars, Libya) (Fig. 7).

Excluding Turkey, almost all the marine aquaculture production in 2009 was undertaken by northern Mediterranean countries, especially Greece, Italy, Spain and France (upper panel in Fig. 8). The brackish production was completely dominated by Egypt and Italy (middle panel in Fig. 8). The freshwater production was also dominated by Egypt, followed by Turkey, France, Italy, Spain and Israel (lower panel Fig. 8).

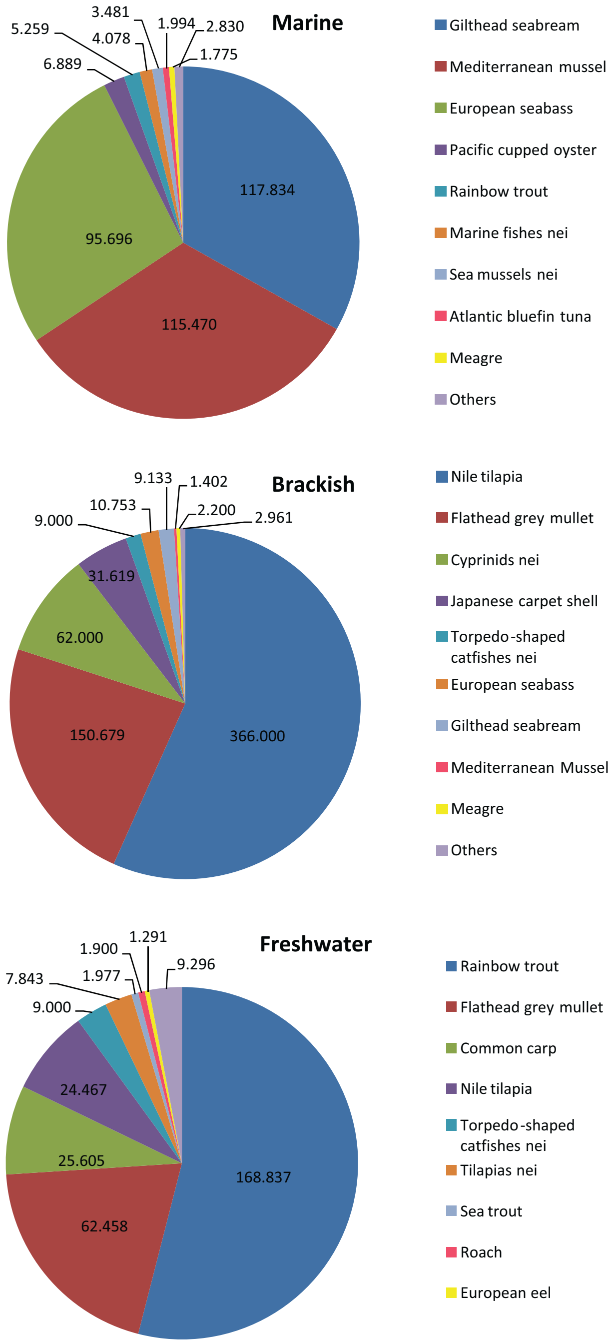

Figure 6 Main species produced (tonnes) in the marine, brackish and freshwater aquaculture systems of the Mediterranean Sea in 2009 (*source*: FAO Fishstat).

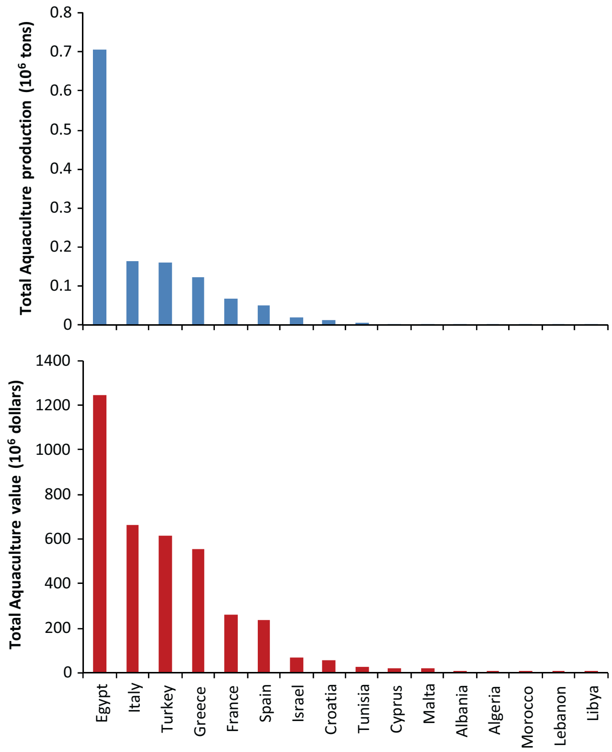

Figure 7 Aquaculture production (quantity and value) of the Mediterranean countries in 2009 (*source*: FAO Fishstat). *Note*: Serbia and Montenegro have not shown any production in that year.

Production systems

The diversified character of Mediterranean aquaculture is based on geographical differences, together with a range of historical and socio-economic factors. The technology applied has evolved rapidly, both in modifying existing facilities and in developing new projects (e.g. offshore cage technology). In fact, production techniques are very diverse, ranging from extensive to highly intensive systems, involving valli systems, earth ponds, floating cages, or raceways or tanks. Cages are by far the most popular production technique, used in lagoons, sheltered bays or semi-exposed and offshore conditions.

Extensive freshwater aquaculture

This sub-sector is mainly conducted in Mediterranean lakes, rivers and reservoirs, and has been linked to the re-stocking for commercial fisheries and seeding for sport fisheries. These activities are normally supported by public authorities dealing with fisheries and aquaculture, forestry or with agriculture (irrigation). This sector is only relevant in a few countries (e.g. Egypt, Tunisia; several thousands of tonnes per year) and takes place in a wide range of water bodies that differ in size and use (mostly reservoirs used for electricity production or for irrigation), and support a huge number of fishermen either belonging to cooperatives or working individually. The most common species stocked is common carp. Various species of tilapia, pike (*Esox lucius*) and perch-pike (*Stizostedion lucioperca*) are also used frequently. Wild-caught fingerlings of grey mullets (*Mugil cephalus* and *Liza ramada*) are used to

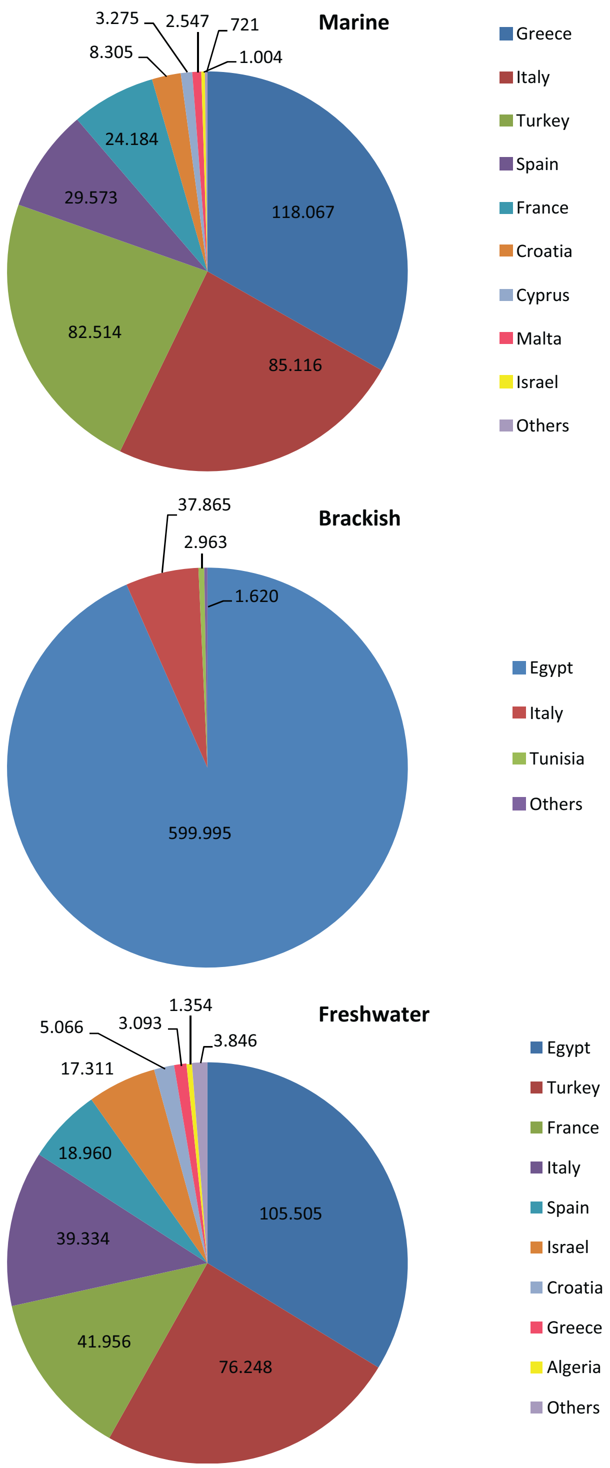

Figure 8 Relative contribution of the main producing Mediterranean countries (values in tonnes) for the marine, brackish and freshwater aquaculture production in 2009 (*source*: FAO Fishstat).

restock reservoirs in southern Mediterranean countries, which have contributed to an increase in freshwater fish production in the late 1990s.

Intensive and semi-intensive inland aquaculture (including integrated aquaculture)

This sub-sector is mainly dominated by trout, carp and tilapia farming. Trout farming (mainly *Oncorhynchus mykiss* and *Salmo trutta*) is concentrated in the EU Mediterranean countries and Turkey, where it represents the most widespread form of intensive inland aquaculture. In the other Mediterranean countries, trout culture is rare because of the limited availability of cold water sources. However, the sector still attracts new investment and, in general, shows a gradual expansion (FAO 2011).

Carp aquaculture, which is based on the rearing of common carp and introduced Chinese carps, was developed traditionally in the Eastern European countries where, for a long period of time, it was the most widespread aquaculture practice. Egypt and Israel are the only other Mediterranean countries that base their production mainly (70–80%) on inland aquaculture, with carp and tilapia farming. In addition, Egypt also produces mullets, sea bass and, due to the presence of low salinity inland waters, sea bream. Inland semi-intensive and intensive aquaculture is usually combined, in ponds and canals, with water used for irrigation. Both countries reported a progressive intensification of production (from semi-intensive to intensive pond management) to limit water consumption. This process of intensification appears to be more urgent in Israel, because of the limited availability of freshwater, but more dramatic in Egypt, where it involves the elimination or restoration of the most primitive production units that represent about 70% of the farmed area (FAO 1999). Intensive or hyper-intensive eel culture was reported by Italy and Greece. However, this activity is significantly constrained by the limited availability of wild seed (glass eels). Egypt is the only Mediterranean country that reported the development of integrated aquaculture (rice–fish cultivation) stating, however, that its existence depends highly on governmental subsidies (often in the form of free fingerlings supply). However, production has gone down significantly now that fingerlings are no longer distributed free.

Inshore aquaculture

Inshore aquaculture represents the bulk of coastal aquaculture production, having been developed in protected areas such as bays, gulfs, canals and coastal lagoons, mostly based on mollusc farming and finfish cage culture. Despite the fact that it is subject to the same numerous constraints to on-land aquaculture (e.g. deterioration in coastal water quality), which limit the availability of adequate sites, a few countries still plan a significant expansion of inshore aquaculture, as well as its gradual transfer into open waters (see next section). Mollusc culture, which has been developed since the beginning of the 20th century, involves the use of various techniques (fixed and floating structures) basically for the production of mussels (*Mytilus galloprovincialis*) and oysters (*Crassostrea gigas* and *Ostrea edulis*). Other species, such as scallops, clams and abalone, have also been farmed in order to diversify the production, but none attained the same commercial scale as mussel and oyster rearing. In particular, the promising culture of the imported Japanese carpet shell was strongly constrained by its rapid adaptation to the natural environment, which gave rise to a competitive fisheries production. Mollusc culture is highly developed in the EU Mediterranean countries (Spain, France, Italy and Greece, with a total of several hundred thousands tonnes per year), also relying on a traditional domestic consumption of these species groups. The sector has reached a high level of technology and mechanization, and farms are operated both by private and corporate producers.

The cage farming of marine finfish started in the early 1980s. This inshore activity provided the opportunity to avoid expensive land-based facilities but was initially confined to protected coastal areas until the more recent development of reliable offshore cages. This farming technique therefore appears to be highly constrained by the competitive use of the littoral zone, and it is not expected to show further significant expansion. Greece, Turkey, Italy, France, Spain and Croatia (Fig. 8) are the most important producers of marine fish in the Mediterranean, using inshore cage farming. Marine fish farming is mostly developed by private enterprises and less so by corporate groups.

Offshore aquaculture

This form of aquaculture has the potential to solve most of the difficulties that hamper the expansion of coastal aquaculture, and therefore attracts great interest in most Mediterranean countries. Conflicts with the tourism industry or scarcity of appropriate sites forced the producers to move far from the coast. As a result, most production of intensive marine finfish aquaculture in the Mediterranean takes place today in (semi) offshore floating cages (open sea system). This system type has been preferred to land based facilities, but requires high capital investments and has high running costs. Yet, in the right site, open sea culture offers a better environment for fish welfare, and for intensive marine aquaculture is believed to have fewer negative impacts on the environment. Most cages are situated in semi-offshore sites at depths between 15 and 30 m. In Spain, gilthead seabream and European seabass are mainly produced in offshore cage systems along the Mediterranean coast and in the Canary Islands. The cages are floating, circular, structures of the same type used throughout the Mediterranean. In Greece, close to 80% of the aquaculture fish is cultured in cages, with the remaining 20% produced in land-based raceways. Nonetheless, many countries still have no local suppliers and must import cages and equipment from abroad. The increased management costs related to the daily routine operations concerning cages located far from the coast is also limiting offshore aquaculture development. Offshore aquaculture has also been used, but at a lesser extent, for mussel production (in long lines). High investment and management costs are also required, namely strong mooring systems and long line structures, as well as large workboats.

Climate change and Mediterranean aquaculture

Temperature

Since 1970, south-western Europe has reported a temperature rise of about 2°C (Tourre *et al.* 2008). Yet, by the end of the 21st century, an increase in air temperature between 2.2°C and 5.1°C is expected in the Mediterranean region (IPCC 2007, scenario A1B). This warming will have diverse impacts on aquaculture, depending on the production system, farmed species and country/region. The intensive and semi-intensive inland aquaculture (see above) in northern (EU) Mediterranean countries is dominated by trout farming. These fish species have a very narrow optimal range of temperature and a relatively low upper thermal limit, and consequently, warming may significantly enhance trout mortality and affect productivity (Ficke *et al.* 2007). On the other hand, southern countries, such as Egypt, base their inland production on tilapia farming, a group of fish with a wider optimal range of temperature and higher thermal limits. Analyses of current climatic trends reveal a warming trend in Egypt, with increases of 1.4°C and 2.5°C projected to 2050 and 2100, respectively (Agrawala *et al.* 2004). The expected water temperature rise will result in increased metabolism, growth rates and hence in overall production. Yet, it is worth noting that higher temperatures in the semi-arid regions with resulting evaporative losses coupled with increasing water demands will likely result in decreasing water availability from the Nile (Agrawala *et al.* 2004). Moreover, the increased air temperature may also enhance vaporization and cloud cover, and, consequently, reduce solar radiation (IPCC 2007). As a result, this may not induce any predicted enhancement in pond-based production. It is worth noting that increased temperatures may also affect pond evaporation rates, especially in Mediterranean North Africa, and the resultant increases in pond salinity could adversely affect less salt-tolerant species.

Eutrophication and harmful algae blooms

Increased eutrophication and pronounced stratification in Mediterranean lenthic systems is expected in the future. These processes lead to oxygen depletion in the dawn hours and sudden wind- and rainfall-driven upwelling processes bring the hypoxic waters to the surface, with consequent deleterious effects to the cultured stocks (Cochrane *et al.* 2009).

Many coastal areas in the Mediterranean Sea are eutrophic, especially in semi-enclosed areas (UNEP/FAO/WHO 1996). The use of satellite imagery on chlorophyll distribution shows that the very high concentrations are located close to river deltas and estuaries or near urban agglomerations, especially in the estuary of the Nile (from Alexandria to Gaza), Gulfs of Antalya and Alexandretta (Turkey), Northern Aegean, Thermaikos Gulf (Greece), the Adriatic Sea, the Gulf of Lions (France), Valencia-Barcelona (Spain) and the Gulf of Gabes (Tunisia). Increased temperatures associated with eutrophication can enhance the occurrence of toxic tides, i.e. harmful algae blooms (HABs) (Dale *et al.* 2006; Hinder *et al.* 2012), have a negative impact on aquaculture production (especially the farming of filter feeders) and increase human health risks. In fact, the human consumption of seafood contaminated with harmful biotoxins results in a variety of illnesses with varying degrees of severity, including amnesic shellfish poisoning (ASP), diarrhoetic shellfish poisoning (DSP) and paralytic shellfish poisoning (PSP). Biotoxins primarily target the nervous system, but can also result in potentially fatal acute respiratory distress and other chronic neurological and immunological illnesses. The danger of inadvertently consuming biotoxins is compounded by the fact that they are odour-free and tasteless and are unaffected by food preparation procedures (see Marques *et al.* 2010).

Extreme events and water stress

The impacts of climate change on the Mediterranean environment will relate particularly to water, via a change of its cycle due to a rise in evaporation and a decrease in rainfall. Extreme events, such as heat waves, droughts or floods, are likely to be more frequent and violent. A significant decrease in rainfall, ranging between −4% and −27% for the countries of Southern Europe and the Mediterranean region is expected (while the countries of Northern Europe will report a rise between 0% and 16%) (IPCC 2007, scenario A1B). Concomitantly, an increase in drought periods related to the high frequency of days during which the temperature would exceed 30°C is also predicted (Giannakopoulos *et al.* 2005; Tourre *et al.* 2008).

This water problem will be of crucial importance with regard to the issue of sustainable development in the region. Floods (resulting from altered rainfall patterns) will affect nutrient loads in the coastal aquaculture areas. High inorganic sediment loads can reduce or arrest the filtration rates of bivalves. Elevated nutrient levels can also stimulate HABs. For coastal and offshore aquaculture, more frequent and intense storms result in increased physical damage and stock losses, both of which are costly to operations. Many coastal processes, such as sediment transport, happen mostly during high-energy events (storms). An increase in storm activity may therefore initiate erosion. Any severe flooding event could result in mass mortalities of animals in aquaculture ponds, open-water rafts, and lines or cages in coastal and offshore areas. Regarding drought, over much of the Mediterranean basin the general tendency is towards decreasing rainfall. The predicted water stress is thought to result in decreasing water availability in the major Mediterranean freshwater systems, areas where there are important aquaculture activities (see production in Fig. 6).

Sea level rise

Rising global temperatures are very likely to raise the sea level by expanding ocean water and melting mountain ice caps and glaciers (IPCC 2007). Based on the existing models available for assessment, the central values for projections of sea level rise by 2100 in the Mediterranean Sea range from about 30–40 cm (Marcos *et al.* 2009), and about 60% of this increase would be due to the thermal expansion of sea water (Tourre *et al.* 2008). This rise is expected to destroy areas where sand belts are essential for the protection of lagoons and other low-lying areas. A significant part of Mediterranean aquaculture activities occur in the deltaic areas (e.g. Nile) and estuaries, at the middle to upper levels of the tidal ranges. Sea level rise, coupled with increased saline water intrusion, will change the water quality and affect most freshwater and brackish production. Higher temperatures and evaporation would also cause rises in the salinity of lakes and reservoirs. In Malta, a 1 m rise in sea level could reduce water from the main reservoir by 40% (Attard *et al.* 1996), while in France, the Vaccares and lower lakes of the Camargue are anticipated to become hypersaline (Corre 1992). Problems of saline intrusion would be further exacerbated by reductions in runoff and by increased withdrawals in response to higher demand. Excessive demand already contributes to saline intrusion problems in many coastal areas of Italy, Spain, Greece and North Africa (Aru 1996). Changing production to more salinity tolerant strains and/or to farming saline tolerant species, are possible adaptive measures to these problems. Yet, such shifts are going to be costly and will also impact on the socio-economic status of the Mediterranean communities involved.

Acidification

In the year 2000, 72% of the Mediterranean greenhouse gases emissions were due to CO_2 connected with energy use (77% in the northern Mediterranean countries and 64% in the southern countries) (Tourre *et al.* 2008). In 2025, the CO_2 emissions due to energy use will be twice as high as they were in 1990. The share of the southern countries in the total emissions generated in the Mediterranean would be about 50% in 2025. In 2006, the northern Mediterranean countries accounted for about two-thirds of the CO_2 emissions due to energy use of the whole Mediterranean basin (Tourre *et al.* 2008). However, the growth of CO_2 emissions seems to be far more rapid in the south than in the north. Indeed, while the northern part reported an increase of 18% between 1990 and 2004, the emissions of the southern rim increased by 58% over the same period. This growth rate is 20 points higher than the world rate.

Although the oceanic uptake of anthropogenic CO_2 will lessen the extent of global warming, the direct effect of CO_2 on ocean chemistry may affect marine biota profoundly (Kleypas *et al.* 2006; Fabry *et al.* 2008; Rosa & Seibel 2008; Doney *et al.* 2009). In fact, future changes in the chemistry of Mediterranean Sea may pose particular problems for marine organisms with $CaCO_3$ shells and skeletons. The degree to which these organisms are affected depends largely upon the $CaCO_3$ saturation state. With increasing seawater pCO_2 both pH and carbonate availability will decrease in the Mediterranean Sea, which may result in reduced calcification rates and shell dissolution (Michaelidis *et al.* 2005a,b; Gazeau *et al.* 2007). In order accurately to assess the socio-economic and ecological impacts of ocean acidification, it is urgent to investigate the adaptive response of calcareous organisms to long-term CO_2 enrichment and the interactive effect of the concomitant increase in seawater temperature. Although some studies highlighted the negative effect of seawater acidification on calcification by benthic molluscs under projected atmospheric CO_2 rising scenarios by the end of this century, longer-term studies still need to be achieved in order to take into account a potential adaptation of the organisms to low pH environments.

Diseases

Disease will be a primary constraint to the future growth of many farmed species in the Mediterranean Sea. The future physical and chemical changes may influence the prevalence and potency of marine pathogens and biotoxins, with serious ecological and socio-economic ramifications. Parasites, bacteria, viruses and biotoxins compromise the health of marine and freshwater organisms and therefore are key regulators of marine populations and habitats in aquatic ecosystems.

Mediterranean aquaculture is expected to be threatened by pathogen range expansions induced by a changing climate as increased temperatures stimulate the growth, transmission and survival of aquatic parasites. Rising sea surface temperatures will afford aquatic parasites the conditions necessary to proliferate in areas where previously they were inhibited by lower temperature thresholds (Ward & Lafferty 2004; Handisyde *et al.* 2006). Additionally, aquaculture practice unnaturally increases host densities, thereby making species even more vulnerable to infectious diseases (Snieszko 1974). Yet, the geographical spread of parasites (and their hosts) will inevitably be moderated by a variety of ecological and environmental factors, rising temperatures notwithstanding (Harvell *et al.* 1999, 2002; De Silva & Soto 2009). Aquatic diseases in the Mediterranean basin will adversely affect human health through the consumption of contaminated seafood and the ingestion of water-borne pathogens. Although the transmission of these diseases is influenced by a variety of social, economic and ecological conditions and human immunity, climatic conditions will play an increasingly important role.

Bacterial and viral fish diseases

It is expected that most future disease reports in the Mediterranean basin will be related to finfish intensive production, especially seabass and seabream in marine systems and trout in freshwater systems. It is worth noting that scarce information has been obtained about diseases occurring in the extensive and semi-intensive systems of the southern margin of the Mediterranean basis (i.e. in tilapia, carp and mullet).

The main diseases reported in the Mediterranean region are vibriosis, pasteurellosis, enteric red mouth (ERM) disease, furunculosis and marine flexibacteriosis. Within the genus *Vibrio*, the species causing the most economically serious diseases in marine culture are *Vibrio anguillarum*, *V. vulnificus*, *V. ordalii* and *V. salmonicida*, the first two being the most significant diseases for the Mediterranean region (Arias *et al.* 1995, 1997). The ERM is the most reported disease in trout farming in Mediterranean countries. The typical furuncolosis is described in both freshwater fish (mainly cultured salmonids) and marine fish (mainly seabass, seabream and turbot). Other significant diseases, with lower reports are rainbow trout fry syndrome (RTFS), columnaris disease, motile *Aeromonas septicemia*, pseudomoniasis, streptococcocis, mycobacteriosis, epitheliocystis and rainbow trout gastrointestinal syndrome (RTGS) (Rodgers & Furones 1998; Le Breton 1999; Ariel & Olesen 2002; Toranzo 2004).

About nine viruses, namely lymphocystis, nodavirus, infectious pancreatic necrosis (IPN), infectious haematopoietic necrosis (IHN), viral haemorrhagic septicaemia (VHS), spring viraemia of carp (SVC), catfish iridovirus, catfish herpervirus and eel herpervirus have been reported for the Mediterranean area, although only six represent some threat (see Barja 2004). Yet, it is difficult to predict which viruses are going to enhance or decrease in virulence and pathogenicity in the future climate scenarios.

Fish parasitic diseases

In the Mediterranean Sea, there are about 35 different parasitic diseases (Table 1), which is significantly higher than those reported for fish bacterial and viral diseases (see previous section).

The main parasitic diseases in freshwater fish (salmonids, cyprinids and eels) are trichodiniasis, costiasis, white spot diseases, *Dactylogyrus* and gyrodactilosis. The main parasitic diseases in marine fish (seabass, seabream, turbot, other sparids, etc.) are trichodiniasis, costiasis, *Enteromyxum leei*, *Ceratomyxa*, amyloodiniosis, mycrocotylosis and sea lice disease. There is an increasing concern of parasitic diseases in intensively cultured finfish in the Mediterranean area, since some parasites can be considered a serious threat for mariculture, such as *Amyloodinium* (Dinoflagellates), Scuticociliatida (Ciliates), *Enteromyxum* spp. (Myxosporea) or Mycrocotylidae (Monogenea). Other parasites are rarely reported in mortality episodes. However, their pathological concern should not be neglected, considering their increasing presence in the cultures and their direct or indirect effects, even when they are not the direct cause of mortality (Alvárez-Pellitero *et al.* 1993, 1995; Rodgers & Furones 1998; Le Breton 1999; Ariel & Olesen 2002; Alvárez-Pellitero 2004; Athanassopoulous *et al.* 2009). Future climate change may allow, by altering the transmission dynamics of these parasites, diseases to emerge without the need for evolutionary changes in the ability of a parasite to use the host (Hatcher & Dunn 2011). Yet, although disease transmission may be affected by climate, other factors such as host immunity, competition and predation will play a role in disease control.

Table 1 Main reported fish parasites/diseases in the Mediterranean Sea

Major group	Parasite/disease	Most frequent fish host
Amoebozoan	Amoebiasis	1,2,3,4
Dinoflagellates	Amyloodiniosis	1,2
Flagellates		
Ectoparasitic	Costiasis, cryptobiasis	Freshwater and marine nei
Endoparasitic	*Trypanosoma* sp., Hexamitiasis	3,5
Ciliates	Chilodonellosis	Freshwater nei
	Cryptocaryosis	2,6
	Trichodiniasis	1,2,5,7
	White spot disease	3
	Scuticociliatida	1,2,4
Protozoans	Coccidiosis	1,2,4,6
	Microsporidiosis	1,4,6,8
Myxosporea	Whirling disease	3
	Proliferative kidney disease (PKD)	3
	Sphaerospora renicola	5
	Ceratomyxa spp.	1,2
	Enteromyxum leei	1,6
	Enteromyxum scophthalmi	4
	Sphaerospora dicentrarchi	1
	Sphaerospora testicularis	2
Monogenea	*Gyrodactylus* spp.	1,2,3,5
	Dactylogyrus spp.	3,5,7
	Diplectanum spp.	1,2
	Furnestinia spp.	1,2
	Microcotylosis	1
Trematoda	*Diplostomum* spp.	3,5
Digenea	Sanguinicolosis	1,5
Cestodes	Pseudophyllidea	Freshwater nei
	Protecephalidea	Freshwater nei
Crustaceans	Copepoda	1,2,3,5
	Isopoda	2,6

Adapted from Alvárez-Pellitero (2004); Athanassopoulous *et al.* (2009). 1, Seabream; 2, seabass; 3, salmonids; 4, turbot; 5, cyprinids; 6, other sparids; 7, eel; 8, mugilids. nei, not elsewhere identified.

Mollusc diseases

As discussed in previous sections, the main mollusc species produced in the Mediterranean region are the Mediterranean mussel, the blue mussel, the Pacific cupped oyster, the Japanese carpet shell clam and the European flat oyster. The main diseases that have been reported for these species are bonamiosis, marteiliosis, perkinsosis, haplosporidiosis, mytilicolosis, brown ring disease, larval/juvenile vibriosis and herpes-like virus infection (see Berthe 2004), but which of these (or new ones) are going to prevail and to have a greater incidence within the predicted climate change scenarios is difficult to predict.

Drug and chemical use

Measures to combat diseases of farmed fish and shellfish have only recently assumed a high priority in many Mediterranean countries. For the treatment of disease or pathogen eradication, most of them still rely on chemotherapeutants, especially for the control of infectious microbial diseases of finfish (Daniel 2009; Subasinghe 2009). Prophylactic drugs are used to minimize diseases caused by opportunistic infectious agents, and to prevent spread via personnel and equipment. Chemotherapy has value in preventing and controlling aquatic animal diseases, but must be used in a judicious manner. In addition to the direct threat of aquatic pathogens to sympatric wild populations, the confluent nature of the aquatic environment means that the use of chemical treatments in some culture systems may also have untargeted effects. Although considered essential for the intensive culture of some species, inappropriate chemical use is coming under increased scrutiny and revised disease management practices. While chemotherapy will perhaps remain one of the main strategies for controlling transmissible diseases in the foreseeable future, especially in finfish, there is increasing recognition of its limitations in terms of host species and pathogen groups against which they are effective (Douet *et al.* 2009; Rodgers 2009). In some cases, rather than providing a solution, they may complicate health management by triggering toxicity, resistance, residues and, occasionally, public health and environmental consequences. In addition to side-effects, the efficacy of chemotherapeutants in certain aquatic environments (e.g. offshore systems) is questionable, both with respect to treatment goals, as well as to the cost of untargeted effects. Occasional misleading claims and advertising regarding the use of antibiotics and other therapeutic drugs has further complicated the use of chemicals for treating health problems.

Vaccination is an alternative prophylactic method to control future disease episodes in Mediterranean aquaculture. While some commercial vaccines have proven effective in providing protection against certain fish diseases (Alderman 2009; Le Breton 2009), vaccination is still not possible against molluscan pathogens. Their development requires considerable research on the target pathogen, as well as any resultant disease, and involves careful planning, field trials and cost evaluation.

Sustainable development and adaptive measures

The development and intensification of Mediterranean aquaculture has revealed a broad spectrum of associated environmental issues. The interaction between aquaculture and the environment is a varied and complex topic, in relation to sustainable development.

Domestication and introduced species

Domestication can contribute to a future sustainable Mediterranean aquaculture since it avoids the need to capture wild stocks. It is noteworthy that the potential impact on the wild ecosystem of fish escapes may be minimized, since cultured organisms can be selected to be unable to survive in wild conditions, dying in a short period of time and with a high percentage of organisms unable to reproduce (sterile organisms) (e.g. Omoto *et al.* 2005; Cal *et al.* 2006; Gagnaire *et al.* 2006). Thus, the advantages of domesticating organisms are to secure seed supply and to improve production efficiency through the mastering of breeding and feeding to select organisms that can grow faster. Concomitantly, it will minimize the potential negative impacts on wild stocks by trying to make cultured organisms unable to live in the wild ecosystems (UNEP/MAP 2005; IUCN 2007). Yet, some negative effects of domestication are related to the emergence of genetic drift and inbreeding problems (Agnese *et al.* 1995), since only a small population of parents is maintained.

An alternative is the introduction of new species, but the risks are quite relevant. The consequences of the escape of those species may dictate major impacts on Mediterranean biodiversity and ecosystems (see McNeely & Schutyser 2003), such as alterations in the genetic diversity of wild populations. Such organisms may compete with native species for food and space, and might also transfer diseases and parasites. In fact, there is already a high number of introduced marine species that are increasing, mainly in ports and lagoons. Over 600 marine exotic species have been recorded in the Mediterranean Sea (UNEP/MAP 2004) and the mode of introduction is different within the basin. In the eastern Mediterranean, penetration via the Suez Canal is the main mode of introduction, while in the western Mediterranean, shipping and aquaculture (to a lesser extent) are responsible for the great majority of exotic species (EEA 2006). The introduction of species should be carried out only in special cases and taking all required precautions. The recommendations and suggestions mentioned in the ICES Code of Practices (2005) as well as in Hewitt *et al.* (2006) should be followed. Regional and international collaboration in the Mediterranean basin should be supported to address trans-boundary biodiversity impacts of introduced species (see UNEP/MAP 2005).

Capture of wild stocks and aquafeeds

One of the most important issues for the future and sustainable development of Mediterranean aquaculture is the sustainability of the source of cultivated fish or shellfish. Aquaculture should help to relieve this pressure on wild stocks and to promote the maintenance of biodiversity, whilst satisfying the growing market demand for aquatic products (IUCN 2007). Therefore, as a principle, the stocking of aquaculture farms should not affect the natural status or viability of wild populations and their ecosystems or biodiversity in general. An example is the expansion of the Atlantic bluefin tuna farming activities in the Mediterranean that has generated a growing demand for wild fish specimens. Hence, one of the main concerns about this demand is the current and potential pressure to increase fishing. In general, it is preferable that organisms that are to be raised in aquaculture farms should have been produced in hatcheries.

Regarding aquafeeds, the Mediterranean market is focused on the production of formulated feeds for intensively produced carnivorous fishes, namely seabass, seabream and trout. Other important fish species, albeit with a much lower production, are turbot, eel and salmon (Martín 1999). Due to the growth in the production of marine fish species, the Mediterranean aquafeed market has significantly grown from an estimated production of 315 000 tonnes in 1995 to 500 000 tonnes in 2001, a 58% increase (Montero *et al.* 2005). It is highlighted that parallel to these increases in the production of aquafeed for marine fish, there has been a substantial improvement in feed efficiency. Practically the whole of the aquafeed market is concentrated in only five countries: Spain, Greece, France, Italy and Turkey. The great development of intensive fish farming in recent years is noteworthy in countries such as Greece and Turkey, meaning an important change in the distribution of the market. The future development of Mediterranean aquaculture is strongly linked to the possibility of providing sustainable aquafeed ingredients. The current marked increase in aquaculture production has to take into account that fish meal and fish oil are worldwide limited resources (Tacon 2004). If the Mediterranean aquaculture of carnivorous species wishes to continue further growth, improvements must be achieved in the feeding of these animals, and alternative raw ingredients for aquafeeds must be found. Partial replacement of fish meal and fish oil in the diets of farmed fish by vegetable proteins and oils is taking place without compromising the fish quality, as well as the health benefits of PUFA $\omega3$ diet (Rosa *et al.* 2010). But the complete substitution or replacement of fish meal by more sustainable and renewable protein sources, such as oilseeds or vegetable meals, has brought up several issues, partially because of an inappropriate amino acid balance and poor protein digestibility (Sargent & Tacon 1999).

Effects on Mediterranean biodiversity

Many societal concerns come from the perceived environmental effects of finfish cages or land based aquaculture production units on the Mediterranean flora and fauna (IUCN 2007). In some cases, aquaculture facilities, especially fish cages, have negative impacts on local fragile or sensitive species, such as seagrass meadows (see reviews in Hemminga & Duarte 2000; Pergent-Martini *et al.* 2006). The marine bottoms where the cages are sited do not receive sunlight, due to shadowing, and this leads to disruption of the local ecosystem. The natural community modifications are also intensified by nutrient loads and epiphyte covering. Consequently, richness tends to decrease close to cages, but also evolves when the distance from them increases (Nash *et al.* 2005; IUCN 2007). In fact, farm operations attract wildlife (mainly predators and scavengers), and fish are the most prevalent among the attracted organisms, which also include birds, marine mammals, sharks and turtles (Nash *et al.* 2005).

The negative impacts of interaction between aquaculture and local biodiversity (flora and fauna) should be avoided at all cost in the future, whilst the positive effects should be exploited. Hydrodynamic and ecological studies should be conducted as part of the process of site selection, and areas that contain significant communities of seagrass meadows should be considered as incompatible with the establishment of aquaculture facilities in the Mediterranean. Last, the settlement of cages in exposed areas, located away from the coastal shore, should be encouraged, and the attraction of local fauna by the aquaculture structures should be part of the management of farms (IUCN 2007).

Policy and planning measures

Planning systems are diverse and complex, but they are critical to the sustainable development of Mediterranean aquaculture. For instance, aquaculture site selection and site management can be facilitated through integrated coastal zone management (ICZM), which is an adaptive process based on clear and transparent governance and thorough knowledge to support decision making (IUCN 2009). Integrated coastal zone management is a tool for decision makers in the planning, zoning and licensing of all human activities and all stakeholder rights in relation to a defined coastal area. In the Mediterranean, the major ICZM issues include uncontrolled urban growth near the coast, tourism and loss of coastal biodiversity (IUCN 2009). Future planning should look at suitable zones for aquaculture development as well as potential zones for the development of aquaculture. In fact, locating and identifying areas of interest or areas that are suitable for aquaculture is a key factor in ensuring the sustainable development of this sector in the Mediterranean. The process facilitates administrative procedures and allows for better management and forecasting of growth (IUCN 2009).

Another priority area for the development of this sector is the ecosystem approach to aquaculture (EAA), which aims to integrate aquaculture within the wider ecosystem in such a way that it promotes sustainability of interlinked social ecological systems. It is a tool for the integrated management of human activities, based on the protection of land, water and living resources; a strategy that promotes conservation and sustainable use of the ecosystem in an equitable way. The EAA emphasizes the need to integrate aquaculture with other sectors (e.g. fisheries, agriculture and urban development) that share and affect common resources (see Shepherd 2004; Soto *et al.* 2008; De Silva & Soto 2009; IUCN 2009).

Conclusions

The Mediterranean region, also known as the cradle of western civilization, has been subject to human intervention for millennia. Due to religious and social traditions,

Table 2 Summary of the effects of climate change in Mediterranean aquaculture and potential adaptive measures

Impact of climate change	Adaptation/mitigation measures
Temperature rise (above optimal range of tolerance)	Use better feeds
	Use selective breeding and genetic improvements
	Use short-cycle aquaculture
Enhanced growth/ production	Increase feed input
Sea level rise/salt water intrusion	Changing farmed species
	Moving operations away from the shore
Increase in eutrophication	Improve monitoring and early warning systems
	Implement waste water treatment with cost-effective and environmental friendly techniques
Limitations on seafood meal and fish oil supplies	Shift to non-carnivorous, bivalve and seaweed species
	Genetic improvement for alternative feeds
Less wild seed stocks	Use of hatchery seed
	Protect nursery habitats
	Improve seed quality and production efficiency
	Close the species life cycle
Water quality	Implement waste water treatment with cost-effective and environmental friendly techniques
	Improve efficiency of water use
	Avoid using contaminated water
	Shift to faster growing seafood species
	Use agro or multitrophic aquaculture
Loss of stocks	Improve site and design to prevent losses and escapes
	Encourage use of indigenous or non-reproducing species
Increase resistance to diseases (increase use of veterinary drugs)	Replace veterinary synthetic drugs by natural control of diseases (e.g. probiotics, green water technique, natural immunostimulants, vaccines)
	Implement genetic improvements for higher resistance
	Shift to resistant farmed species
	Improve management practices
Increase virulence and expansion of contaminants and diseases	Increase biosecurity measures
	More monitoring and early warning systems
	Implement genetic improvements for higher resistance
	Adopt solutions to reduce contaminant load, e.g. processing seafood, cooking, phycoremediation, etc.
	Develop guidelines and predictive modelling tools for stakeholders
Acidification and calcareous shell formation/deposition	Adapt production and handling techniques
	Move to other production zones

seafood is consumed widely in this region, with an average of 16.5 kg/capita/year (quite similar to the global average: 16.7 kg/capita/year), and ranging from 5.2 in Algeria to 40.0 in Spain (FAO 2011). The growth of seafood demand in the Mediterranean is expected to increase in the future, especially in southern countries (Cochrane & de Young 2007). One fourth of the Mediterranean seafood supply comes from aquaculture activities, whereas the remaining is from fisheries.

The Mediterranean aquaculture sector has expanded over the past decades. It increased 77% over the past decade reaching about 1.3 million tonnes in 2009. Along with predicting vulnerable areas, the selection of suitable sites in relation to specific culture methods and species will be valuable in maximizing profit and food production in the face of a changing climate. The impacts of climate change will relate particularly to water availability and/or quality, due to the expected rise in evaporation, decrease in rainfall, and more frequent and violent extreme events (heat waves, droughts or floods) in this region. For adaptation these climate trends, and consequent environmental changes, the key focus on Mediterranean aquaculture will be on selecting suitable species and culture methods. A summary of the most important predicted impacts of climate change in the Mediterranean aquaculture is given in Table 2, with a wide range of adaptation and mitigation strategies that can be implemented to minimize such effects.

Implementing adaptation and mitigation pathways for Mediterranean communities dependent on aquatic ecosystems will need special attention from policy makers and planners. The solution to climate change is not straight forward, and many extrinsic factors to the aquaculture sector have to be integrated collectively, with an ecosystem perspective.

References

Agnese J-F, Oteme ZJ, Gilles S (1995) Effects of domestication on genetic variability, fertility, survival and growth rate in a tropical siluriform: *Heterobranchus longifilis* Valenciennes 1840. *Aquaculture* **131**: 197–204.

Agrawala S, Moehner A, El Raey M, Conway D, van Aalst M, Hagenstad M *et al.* (2004) *Development and Climate Change in Egypt: Focus on Coastal Resources and the Nile*. Organisation for Economic Co-operation and Development (OECD), OM/ENV/EPOC/DCD/DAC (2004)1, Paris.

Alderman DJ (2009) Control of the use of veterinary drugs and vaccines in aquaculture in the European Union. In: Rodgers C, Basurco B (eds) *The Use of Veterinary Drugs and Vaccines in Mediterranean Aquaculture. Options Méditerranéennes, Série A* **86**: 13–28.

Alvárez-Pellitero P (2004) Report about fish parasitic diseases. In: Alvarez-Pellitero P, Barja JL, Basurco B, Berthe F, Toranzo AE (eds) *Mediterranean Aquaculture Diagnostic Laboratories*. *Options Méditerranéennes, Série B: Etudes et Recherches* **49**: 103–130.

Alvárez-Pellitero P, Sitjà-Bobadilla A, Franco-Sierra A (1993) Protozoan parasites of wild and cultured sea bass, *Dicentrarchus labrax*, from the Mediterranean area. *Aquaculture Fish Management* **24**: 101–108.

Alvárez-Pellitero P, Sitjà-Bobadilla A, Franco-Sierra A, Palenzuela O (1995) Protozoan parasites of gilthead sea bream (*Sparus aurata*) from different culture systems in Spain. *Journal of Fish Diseases* **18**: 105–115.

Arias CR, Garay E, Aznar R (1995) Nested PCR method for rapid and sensitive detection of *Vibrio vulnificus* in fish, sediments, and water. *Applied Environmental Microbiology* **61**: 3476–3478.

Arias CR, Verdonck L, Swings J, Garay E, Aznar R (1997) Intraspecific differentiation of *Vibrio vulnificus* biotypes by amplified fragment length polymorphism and ribotyping. *Applied Environmental Microbiology* **63**: 2600–2666.

Ariel E, Olesen NJ (2002) Finfish in aquaculture and their diseases – a retrospective view on the European Community. *Bulletin of the European Association of Fish Pathologists* **22** (2): 72–85.

Aru A (1996) The Rio Santa Lucia site: an integrated study of desertification. In: Brandt CJ, Thornes JB (eds) *Mediterranean Desertification and Land Use*, pp. 189–206. John Wiley and Sons, Chichester.

Athanassopoulous F, Pappas IS, Bitchava K (2009) An overview of the treatments of parasitic disease in Mediterranean aquaculture. *Options Méditerranéennes, Série A* **86**: 65–83.

Attard DJ, Axiak V, Borg SF, Cachia J, De Bono *et al.* (1996) Implications of expected climatic changes for Malta. In: Jeftic L, Keckes S, Pernetta JC (eds) *Climate Change and the Mediterranean, Volume 2*, pp. 323–430. Arnold Press, London.

Barja JL (2004) Report about fish viral diseases. In: Alvarez-Pellitero P, Barja JL, Basurco B, Berthe F, Toranzo AE (eds) *Mediterranean Aquaculture Diagnostic Laboratories*. *Options Méditerranéennes, Série B: Etudes et Recherches* **49**: 91–101.

Berthe F (2004) Report about mollusk diseases. In: Alvarez-Pellitero P, Barja JL, Basurco B, Berthe F, Toranzo AE (eds) *Mediterranean Aquaculture Diagnostic Laboratories*. *Options Méditerranéennes, Série B: Etudes et Recherches* **49**: 33–48.

Cal RM, Vidal S, Gómez C, Álvarez-Blázquez A, Martínez P, Piferrer F (2006) Growth and gonadal development in diploid and triploid turbot (*Scophthalmus maximus*). *Aquaculture* **251**: 99–108.

Cochrane K, de Young C (2007) Ecosystem approach to fisheries management in the Mediterranean. *Cahiers Options Mediterraneenes* **62**: 71–85.

Cochrane K, De Young C, Soto D, Bahri T (2009) *Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge*. FAO Fisheries and Aquaculture Technical Paper. No. 530. FAO, Rome, 212 p.

Corre JJ (1992) Implications des changements climatiques etude de cas: Le Golfe du Lion (France). In: Jeftic L, Milliman JD, Sestini G (eds) *Climatic Change and the Mediterranean*, pp. 328–427. Arnold Press, London.

Dale B, Edwards M, Reid PC (2006) Climate change and harmful algal blooms. *Ecological Studies* **189F**: 67–378.

Daniel P (2009) Available chemotherapy in Mediterranean fish farming: use and needs. In: Rodgers C, Basurco B (eds) *The Use of Veterinary Drugs and Vaccines in Mediterranean Aquaculture*. *Options Méditerranéennes, Série A* **86**: 197–205.

De Silva SS, Soto D (2009) Climate change and aquaculture: potential impacts, adaptation and mitigation. In: Cochrane K, Young C, De Soto D, Bahri T (eds) *Climate Change Implications for Fisheries and Aquaculture Overview of Current Scientific Knowledge*. FAO Fisheries and Aquaculture Technical paper: No. 530, pp. 151–212. FAO, Rome.

Doney SC, Fabry VJ, Feely RA, Kleypas JA (2009) Ocean acidification: the other CO_2 problem. *Annual Review of Marine Science* **1**: 169–192.

Douet DG, Le Bris H, Giraud E (2009) Environmental aspects of drug and chemical use in aquaculture: an overview. In: Rodgers C, Basurco B (eds) *The Use of Veterinary Drugs and Vaccines in Mediterranean Aquaculture. Options Méditerranéennes, Série A* **86**: 105–126.

EEA (2006) Priority issues in the Mediterranean environment. European Environmental Agency Report 4/2006.

Eshel G, Farrel BF (2000) Mechanisms of Eastern Mediterranean rainfall variability. *Journal of Atmospheric Science* **57**: 3219–3232.

Fabry VJ, Seibel BA, Feely RA, Orr JC (2008) Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science* **65**: 414–432.

FAO (1999) *Consultation on the Application of Article 9 of the FAO Code of Conduct for Responsible Fisheries in the Mediterranean Region: Synthesis of the National Reports (TEMP/RER/908/MUL)*. FAO, Rome, 19–23 July.

FAO (2011) *The State of World Fisheries and Aquaculture 2010*. Food and Agriculture Organization of the United Nations, Rome.

Ficke AD, Myrick CA, Hansen LJ (2007) Potential impacts of global climate change on fresh water fisheries. *Reviews in Fish Biology and Fisheries* **17**: 581–613.

Gagnaire B, Soletchnik P, Madec P, Geairon P, Le Moine O, Renault T (2006) Diploid and triploid Pacific oysters, *Crassostrea gigas* (Thunberg), reared at two heights above sediment in Marennes-Oleron Basin, France: difference in mortality, sexual maturation and hemocyte parameters. *Aquaculture* **254**: 606–616.

Gazeau F, Quiblier C, Jansen JM, Gattuso JP, Middelburg JJ, Heip CHR (2007) Impact of elevated CO_2 on shellfish calcification. *Geophysical Research Letters* **34**: L07603.

Giannakopoulos C, Bindi M, Moriondo M, LeSager P, Tin T (2005) *Climate Change Impacts in the Mediterranean*

Resulting from a 2°C Global Temperature Rise. WWF Report for a Living Planet. The Global Conservation Organization, Gland, Switzerland.

Goudie A (2001) *Encyclopedia of Global Change: Environmental Change and Human Society*, Volume 1. Oxford University Press, Oxford.

Handisyde NT, Ross LG, Badjeck M-C, Allison EH (2006) *The Effects of Climate Change on World Aquaculture: A Global Perspective*. Final Technical Report, DFID, Aquaculture and Fish Genetics Research Programme, Stirling Institute of Aquaculture, Stirling, UK, 151.

Harvell CD, Kim K, Burkholder JM *et al.* (1999) Emerging marine diseases – climate links and anthropogenic factors. *Science* **285**: 1505–1510.

Harvell CD, Mitchell CE, Ward JR, Altizer S, Dobson AP, Ostfeld RS *et al.* (2002) Climate warming and disease risks for terrestrial and marine biota. *Science* **296**: 2158–2162.

Hatcher MJ, Dunn AM (2011) *Parasites in Ecological Communities. From Interactions to Ecosystems*. Cambridge University Press, Cambridge.

Hemminga MA, Duarte CM (2000) *Seagrass Ecology*. Cambridge University Press, Cambridge.

Hewitt CL, Campbell ML, Gollasch S (2006) *Alien Species in Aquaculture. Considerations for Responsible Use*. IUCN, Gland, Switzerland and Cambridge, UK.

Hinder SL, Hays GC, Edwards M, Roberts EC, Walne AW, Gravenor MB (2012) Changes in marine dinoflagellate and diatom abundance under climate change. *Nature Climate Change* **2**: 271–275.

Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* **269**: 676–679.

Hurrell JW (1996) Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. *Geophysical Research Letters* **23**: 665–668.

ICES (2005) *ICES Code of Practice on the Introductions and Transfers of Marine Organisms*. International Council for the Exploration of the Seas, Copenhagen. Available from URL: http://www.ices.dk/reports/general/2004/icescop2004.pdf (accessed 24 September 2011).

IPCC (2007) *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, New York.

IUCN (2007) *Guide for the Sustainable Development of Mediterranean Aquaculture. Interaction Between Aquaculture and the Environment*. IUCN, Gland, Switzerland and Malaga, Spain.

IUCN (2009) *Guide for the Sustainable Development of Mediterranean Aquaculture 2*. Aquaculture site selection and site management, IUCN, Gland, Switzerland and Malaga, Spain.

Jeftic L, Keckes S, Pernetta JC (1996) *Climate Change and the Mediterranean. Volume 2. United Nations Environment Programme (UNEP)*. Arnold Press, London.

Kleypas JA, Feely RA, Fabry VJ, Langdon C, Sabine CL, Robbins LL (2006) Impacts of ocean acidification on coral reefs and other marine calcifiers. A guide for future research. Report of a workshop held 18–20 April 2005, St Petersburg, FL, sponsored by NSF, NOAA, and the U.S. Geological Survey.

Le Breton AD (1999) Mediterranean finfish pathologies: present status and new developments in prophylactic methods. *Bulletin of the European Association of Fish Pathologists* **19** (6): 250–253.

Le Breton AD (2009) Vaccines in Mediterranean aquaculture: practice and needs. In: Rodgers C, Basurco B (eds) *The Use of Veterinary Drugs and Vaccines in Mediterranean Aquaculture. Options Méditerranéennes, Série A* **86**: 147–154.

Marcos M, Tsimplis MN, Shaw AGP (2009) Sea level extremes in Southern Europe. *Journal of Geophysical Research* **114** (C1): C01007.

Marques A, Nunes ML, Moore S, Strom M (2010) Climate change and seafood safety: human health implications. *Food Research International* **43** (7): 1766–1779.

Martín A (1999) Aquaculture feed manufacturing practice in Mediterranean countries. *Options Méditerranéennes, Series Cahiers* **37**: 123–128.

McNeely JA, Schutyser F (2003) Invasive species: a global concern bubbling to the surface. In: Dahl A (ed.) *International Conference on the Impact of Global Environmental Problems on Continental and Coastal Marine Waters*. Geneva (Switzerland), 16–18 July 2003, 12 p.

Michaelidis B, Haas D, Grieshaber MK (2005a) Extracellular and intracellular acid-base status with regard to the energy metabolism in the oyster *Crassostrea gigas* during exposure to air. *Physiological and Biochemical Zoology* **78**: 373–383.

Michaelidis B, Ouzounis C, Paleras A, Pörtner HO (2005b) Effects of long-term moderate hypercapnia on acid-base balance and growth rate in marine mussels *Mytilus galloprovincialis*. *Marine Ecology Progress Series* **293**: 109–118.

Montero D, Basurco B, Nengas I, Alexis M, Izquierdo M (2005) Mediterranean fish nutrition. *Cahiers Options Méditerranéennes* **63**: 158.

Nash CE, Burbridge PR, Volkman JK (eds) (2005) *Guidelines for Ecological Risk Assessment of Marine Fish Aquaculture*. U.S. Department of Commerce, NOAA Technical Memo. NMFSNWFSC-71, Seattle, 90 p.

Omoto N, Maebayashi M, Adachi S, Arai K, Yamauchi K (2005) Sex ratios of triploids and gynogenetic diploids induced in the hybrid sturgeon, the bester (*Huso huso* female × *Acipenser ruthenus* male). *Aquaculture* **245**: 39–47.

Peixoto JP, De Almeida M, Rosen RD, Salstein DA (1982) Atmospheric moisture transport and the water balance of the Mediterranean Sea. *Water Resources Research* **18**: 83–90.

Pergent-Martini C, Boudouresque CF, Pasqualini V, Pergent G (2006) Impact of fish farming facilities on *Posidonia oceanica* meadows: a review. *Marine Ecology* **27**: 310–319.

Rodgers CJ (2009) The risks associated with the use of veterinary drugs and chemicals in aquaculture: assessment and control. In: Rodgers C, Basurco B (eds) *The Use of Veterinary Drugs and Vaccines in Mediterranean Aquaculture*. *Options Méditerranéennes, Série A* **86**: 127–145.

Rodgers CJ, Furones MD (1998) Disease problems in cultured marine fish in the Mediterranean. *Fish Pathology* **33** (4): 157–164.

Rodo X, Baert E, Comin FA (1997) Variations in seasonal rainfall in southern Europe during present century: relationships with the North Atlantic Oscillation and the El Nino Southern Oscillation. *Climate Dynamics* **13**: 275–284.

Rosa R, Seibel BA (2008) Synergistic effects of climate-related variables suggest future physiological impairment in a top oceanic predator. *Proceedings of the National Academy of Science of USA* **105**: 20776–20780.

Rosa R, Andrade AM, Bandarra NM, Nunes ML (2010) Physiological and biochemical effects of conjugated linoleic acid and its use in aquaculture. *Reviews in Aquaculture* **2**: 59–72.

Sargent JR, Tacon AG (1999) Development of farmed fish: a nutritionally necessary alternative to meat. *Proceedings of the Nutrition Society* **58**: 377–383.

Shepherd G (2004) *The Ecosystem Approach: Five Steps to Implementation*. The World Conservation Union (IUCN), Gland, Switzerland.

Snieszko SF (1974) The effects of environmental stress on outbreaks of infectious diseases of fishes. *Journal of Fish Biology* **6** (2): 197–208.

Soto D, Aguilar-Manjarrez J, Brugère C *et al.* (2008) *Applying an Ecosystem-based Approach to Aquaculture: Principles, Scales and Some Management Measures*. FAO Fisheries Proceedings. No. 14, pp. 15–35. FAO, Rome.

Subasinghe R (2009) Disease control in aquaculture and the responsible use of veterinary drugs and vaccines: the issues, prospects and challenges. In: Rodgers C, Basurco B (eds) *The Use of Veterinary Drugs and Vaccines in Mediterranean Aquaculture*. *Options Méditerranéennes, Série A* **86**: 5–103.

Tacon AGJ (2004) Use of fish meal and fish oil in aquaculture: a global perspective. *Aquatic Resources, Culture and Development* **1**: 3–14.

Toranzo AE (2004) Report about fish bacterial diseases. In: Alvarez-Pellitero P, Barja JL, Basurco B, Berthe F, Toranzo AE (eds) *Mediterranean Aquaculture Diagnostic Laboratories*. *Options Méditerranéennes, Série B: Etudes et Recherches* **49**: 49–89.

Tourre Y, Van Grunderbeeck P, Allal H *et al.* (2008) *Climate Change and Energy in the Mediterranean*. Plan Bleu, Regional Activity Center, Sophia Antipolis.

UNEP (1989) *State of the Mediterranean Marine Environment*. MAP Technical Series no. 28. UNEP, Athens.

UNEP/FAO/WHO (1996) *Assessment of the State of Eutrophication in the Mediterranean Sea*. MAP Technical Series no. 106, UNEP, Athens.

UNEP/MAP (2004) Marine pollution indicators Fact. United Nations Environment Programme/Mediterranean Action Plan Document UNEP(DEC)MEDWG.264/Inf.14.

UNEP/MAP (2005) *Action Plan Concerning Species Introductions and Invasive Species in the Mediterranean Sea*. United Nations Environment Programme/Mediterranean Action Plan, Ed. RAC/SPA, Tunis, Tunisia.

Ward JR, Lafferty KD (2004) The elusive baseline of marine disease: are diseases in ocean ecosystems increasing? *PLoS Biology* **2**: 542–547.