Regional Studies in Marine Science 5 (2016) 1–11

Contents lists available at ScienceDirect

Regional Studies in Marine Science

journal homepage: www.elsevier.com/locate/rsma

Impacts of ocean acidification in a warming Mediterranean Sea: An overview

Thomas Lacoue-Labarthe [a,b,*,1], Paulo A.L.D. Nunes [c,d,1], Patrizia Ziveri [e,f], Mine Cinar [g], Frédéric Gazeau [h,i], Jason M. Hall-Spencer [j], Nathalie Hilmi [a,k], Paula Moschella [l], Alain Safa [m], Didier Sauzade [n], Carol Turley [o]

[a] International Atomic Energy Agency — Environment Laboratories, 4 Quai Antoine Ier, Monaco

[b] Littoral Environnement et Sociétés (LIENSs), UMR 7266 CNRS-Université de La Rochelle, Institut du Littoral et Environnement, 2 rue Olympe de Gouges, 17000 La Rochelle, France

[c] Ecosystem Services Economic Unit, Division of Environmental Policy Implementation, United Nations Environment Programme (UNEP), Nairobi, Kenya

[d] Institut de Ciències del Mar, CSIC, Psg. Marítim de la Barceloneta 37-49, Barcelona, Spain

[e] Institute of Environmental Science and Technology, Universitat Autonomòma de Barcelona (UAB), Carretera de les Columnes, S/N, Edifici Z Campus de la UAB, 08193 Bellaterra, Barcelona, Spain

[f] Catalan Institution for Research and Advanced Studies (ICREA), 08010 Barcelona, Spain

[g] Quinlan School of Business, Loyola University Chicago, Chicago, IL 60611, USA

[h] Laboratoire d'Océanographie de Villefranche, CNRS-INSU, BP 28, 06234 Villefranche-sur-Mer Cedex, France

[i] Sorbonne Universités, UPMC Univ Paris 06, Observatoire Océanologique de Villefranche, 06230, Villefranche-sur-Mer Cedex, France

[j] Marine Institute, Plymouth University, Plymouth PL4 8AA, United Kingdom

[k] Centre Scientifique de Monaco, Avenue Saint-Martin, 98000 Monaco, Monaco

[l] The Mediterranean Science Commission, CIESM, Monaco

[m] Skill Partners, Nice, France

[n] Plan Bleu, Villa Valmer, 271 Corniche Kennedy, 13007 Marseille, France

[o] Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, United Kingdom

HIGHLIGHTS

- This paper reviews the current pressures the Mediterranean Sea undergoes including ocean acidification.
- It points out the future challenges that Mediterranean people will have to face with respect to marine resources.
- The manuscript gathers conclusive remarks for the development of strategies to limit the impact of ocean acidification.

ARTICLE INFO

Article history:
Received 17 December 2014
Received in revised form
15 December 2015
Accepted 18 December 2015
Available online 21 December 2015

Keywords:
Mediterranean
Climate change
Warming
Acidification

ABSTRACT

Mediterranean Sea fisheries supply significant local and international markets, based largely on small pelagic fish, artisanal fisheries and aquaculture of finfish (mainly seabass and seabream) and shellfish (mussels and oysters). Fisheries and aquaculture contribute to the economy of countries bordering this sea and provide food and employment to coastal communities employing *ca* 600,000 people. Increasing temperatures and heat wave frequency are causing stress and mortality in marine organisms and ocean acidification is expected to worsen these effects, especially for bivalves and coralligenous systems. Recruitment and seed production present possible bottlenecks for shellfish aquaculture in the future since early life stages are vulnerable to acidification and warming. Although adult finfish seem able to withstand the projected increases in seawater CO_2, degradation of seabed habitats and increases in harmful blooms of algae and jellyfish might adversely affect fish stocks. Ocean acidification should therefore be factored into fisheries and aquaculture management plans. Rising CO_2 levels are expected

* Correspondence to: UMR 7266 CNRS-Université de La Rochelle, Institut du Littoral et Environnement, 2 rue Olympe de Gouges, 17000 La Rochelle, France. Tel.: +33 5 46 45 83 88.
E-mail address: tlacouel@univ-lr.fr (T. Lacoue-Labarthe).

[1] Both authors contributed equally to this work.

http://dx.doi.org/10.1016/j.rsma.2015.12.005

Ecosystem services
Fisheries
Habitat loss
Ecosystem vulnerability

to reduce coastal biodiversity, altering ecosystem functioning and possibly impacting tourism being the Mediterranean the world's most visited region. We recommend that ocean acidification is monitored in key areas of the Mediterranean Sea, with regular assessments of the likely socio-economic impacts to build adaptive strategies for the Mediterranean countries concerned.

1. Introduction

The Mediterranean Sea has a restricted exchange of seawater with the Atlantic Ocean via the Strait of Gibraltar in the West and the Black Sea in the East and to a lesser extent with the Red Sea via the Suez Canal (Fig. 1). The region supports cold, temperate and sub-tropical biota and is a so called 'biodiversity hotspot' with 7% of the world's known species living in 0.82% of the ocean area (Bianchi and Morri, 2000). This exceptional biodiversity benefits economic sectors such as tourism and cultural heritage. In addition, aquaculture and fisheries contribute to local and national income going back to thousands of years. Human-induced CO_2 emission is a global phenomena with different regional consequences. The Mediterranean Sea is affected in several ways through climate change and ocean acidification. Mediterranean acidification is already detectable (Meier et al., 2014; Howes et al., 2015) and combined with the rapid warming, the increase frequency of extreme weather events and the rapid increase of human population around its coasts have serious consequences for the region.

2. Mediterranean fisheries and aquaculture

Fisheries and aquaculture in the Mediterranean Sea represent 1% of world landings, and 2% in terms of economic value. While fish catches have remained quite stable since the 1990's, aquaculture has quadrupled in production reaching 20% of production in 2011 (Fig. 2). While aquaculture production is mainly supported by northern European countries, the fishery sector mainly comprises artisanal activities (∼80% of the flotilla; Sacchi, 2011), being more common in southern Mediterranean countries.

2.1. Capture fishery

Pelagic fish account for 53% of the total Mediterranean catch (Fig. 3; about 460,000 t in 2011) with landings dominated by sardine (*Sardina pilchardus*) and anchovy (*Engraulis encrasicolus*) (Fig. 4).

Demersal fish make up 30% of landings, crustaceans 7% and molluscs (including cephalopods) comprise 10% of Mediterranean landings. The striped venus clam, *Chamelea gallina* (around 20,000 t yr^{-1}) is mainly harvested in the Adriatic Sea and constitutes 70% of molluscs landings. Small-scale fisheries dominate (>60%) the fishing sector in the Mediterranean Sea. Capture fisheries and aquaculture in the Mediterranean Sea provide a central source of food and employment: they directly employ 250,000 and 123,000 in fisheries and aquaculture, respectively and employ about 210,000 people for secondary sector (Sacchi, 2011). In this context, it is of foremost importance to assess the impacts of ocean acidification on these two economic sectors.

2.2. Aquaculture

Fish and mollusc production dominates Mediterranean aquaculture although crustaceans are also farmed. The production of gilthead seabream (*Sparus aurata*) has risen rapidly from 3833 t in 1990 to 143,295 t in 2010 (worth approximately US$ 785 million). European seabass (*Dicentrarchus labrax*) production rose from 2944 t in 1990 to 131,509 t in 2010 (valued at US$ 786 million). In 2010, the main producers of gilthead seabream were Greece (43%), Turkey (20%) and Spain (13%), whereas the top three producers of European seabass were Turkey (40%), Greece (28%) and Egypt (12%). In 2010, 81% of the total Mediterranean meagre (*Argyrosomus regius*) production was in Egypt (GFCM, 2013).

The oyster *Ostrea edulis* has been farmed in the Mediterranean since the 1st century BC. But in the 1970s these oysters suffered mass mortalities due to pathogenic protozoans and have been progressively replaced in aquaculture by the Pacific oyster (*Crassostrea gigas*), as it is more resistant. Mediterranean bivalve yields increased greatly between the 1950's and the 1990's and have now stabilized at around 180,000 t yr^{-1} (Fig. 5). Italy produces 67% of the Mediterranean bivalve production, followed by Greece and France (Fig. 5). This production is dominated by the Mediterranean mussel (*Mytilus galloprovincialis*), which represents almost three quarters of the total Mediterranean shellfish production (120,000 t yr^{-1}; Fig. 5(C)). Japanese carpet shell (*Ruditapes philippinarum*; about 35,673 t yr^{-1} with around 98% in Italy) and the Pacific cupped oyster are the other important cultivated species (8000 t yr^{-1} and 300 t yr^{-1} by Spain and France).

3. Human impacts

Multiple global, regional and local drivers are occurring in the Mediterranean Sea and these can have synergistic impacts (Gambaiani et al., 2009). These drivers include warming, invasive species, habitat loss, overfishing and pollution (Sacchi, 2011; CIESM, 2008a; Claudet and Fraschetti, 2010; Coll et al., 2010; Durrieu de Madron et al., 2011) and are already challenging marine organisms, ecosystems and the ecosystem goods and services that these seas are providing to human societies.

3.1. Ocean warming

The mean maximum summer seawater temperature of the Mediterranean Sea has risen by around 1 °C during the last three decades (Marbà and Duarte, 2010) and there has been an increase in the frequency and intensity of marine heat waves (Coma et al., 2009). Seawater warming can kill organisms such as the mussel *Mytilus galloprovincialis* (Anestis et al., 2007; Gazeau et al., 2014) during summer and autumn periods when seawater temperature is above 26–27 °C. Shellfish farmers are being forced to sell their product earlier than they would otherwise wish to avoid harvesting loss mass mortalities during warm-water events (Ramón et al., 2005).

Continued warming is likely to cause mass mortalities of the endemic seagrass *Posidonia oceanica* (Díaz-Almela et al., 2009), invertebrates (Coma et al., 2009), including habitat-forming sponges and corals (Garrabou et al., 2009) as well as early life stages of a wide range of species (Byrne, 2011). In addition, increasing temperatures may also contribute to higher frequencies of disease