The Gulf of Gabes, southern Tunisia: an endemic fish hotspot under threat

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While representing only 0.32% of the global oceanic volume, the Mediterranean Sea, contains 6-8% of all known marine species with an endemism rate of 10% for fishes (Quignard and Tomasini, 2000). The Suez Canal and the Gibraltar Strait that connect the Mediterranean Sea to respectively the Red Sea and the Atlantic Ocean, are two exotic species spillways making this ecosystem the largest receptacle of exotic species in the world (CIESM, 2013; Streftaris *et al.*, 2005).
On a global scale, species invasion has been recognized as a major threat to biodiversity, even though a causal link between the introduction of exotic species and the risk of local extinction has not yet been demonstrated (e.g. Davis, 2003).
There is ample evidence indeed to warrant the claim that exotic invasions can, at the very least, reduce the abundance of native species, alter disturbance regimes and basic ecosystem processes, impose large economic costs, introduce new pathogens to indigenous populations and modify food webs structure and energy flows (e.g. Libralato *et al.*, 2002). Further, native species can be driven to extinction by competitive interactions (e.g. Olden *et al.*, 2006), by predation (e.g. Roemer *et al.*, 2002), or simply by demographic stochasticity when many new individuals enter the community and occupy part of the carrying capacity of native species (Lande, 1993).

Endemic species, that are native species restricted to a given area, are more endangered by exotic invasions because they cannot escape and establish elsewhere. Thus, the intensity of interaction between exotic and endemic species is of major concern for the conservation of biodiversity as it may contribute to the breakdown of the regional distinctiveness of the Earth's biota (Vitousek *et al.*, 1997; MacKinney and Lockwood, 1999). In this respect, the Mediterranean Sea provides exceptional material for a case study by virtue of its biodiversity and its high percentage of endemic species.
The Mediterranean Sea is currently becoming warmer: in the last decades, temperature has been rising in deep and surface waters (Diaz Almela *et al.*, 2007; Schroeder *et al.*, 2013).
The geographic distribution of fish taxa is strongly clustered in the Mediterranean Sea: subtropical species occur in the south-eastern area, where water temperatures are higher than average (Theocharis *et al.*, 1993), whereas cold-adapted species inhabit northern areas (Bianchi and Morri, 2000). However, as a result of global warming, fish species that were typically found in the warm waters of the southern areas have been observed more frequently in the north (Sabatés *et al.*, 2006; CIESM, 2008). In parallel, the abundance of certain boreal species has markedly decreased (Quignard and Raibault, 1993).
The increase of Lessepsian species introductions as well as those of Atlantic species from lower latitudes in correlation with the increasing temperature of the Mediterranean Sea suggest that this sea is acting as a catchment basin for exotic thermophilic species (Ben Rais Lasram and Mouillot,

2009). This is corroborated by the recent invasion of the western basin of the Mediterranean, colder than the other areas, by Lessepsian species.
Moreover, the comparison of exotic fishes richness maps generated more than 20 years apart (before and after the significant climatic warming period), reveals a clear modification in the species distribution pattern. After the 1980s, some exotic fishes reached the coldest areas of the Mediterranean Sea, such as the Adriatic Sea, which is a major hotspot of endemism (Ben Rais Lasram and Mouillot, 2009). The number of exotic species in the Mediterranean is now about double of what it was 20 years ago.

It is now obvious that sea surface warming is expected to drive a general northward shift of fish ranges in the Mediterranean Sea leading to the gradual replacement of cold temperate species by thermophilic species. Hence, the coldest parts of the Mediterranean Sea (Gulf of Lion and northern Adriatic) could initially serve as a sanctuary for cold-temperate species; but, with intensified warming, those areas might become a "dead end", from which cold-temperate species could not escape. This process would be critical to endemic species, because the trapping effect would lead to species extinction (Ben Rais Lasram *et al.*, 2010).
According to projections derived from climatic envelope models for 2041–2060 (Ben Rais Lasram *et al.*, 2010), 53% of endemic fish species would be considered as "looser" i.e. reducing their habitat and 47% would be considered as "winner". By 2070–2099, there would be 64% of looser species and 36% of winner species.
By 2041–2060, 3/4 of the looser species are expected to qualify for the IUCN Red List. 20% of them are expected to become extinct and 20% are expected to become highly threatened. By 2070–2099, 90% of the looser species are expected to qualify for the IUCN Red List. 33% of them are expected to become extinct.
By the middle of the current century, all the species now expected to become extinct would be of low prevalence and encountered in the coldest areas of the Mediterranean Sea (Ben Rais Lasram *et al.*, 2010).

Four scenarios for species predicted to lose part of their geographic range can be distinguished (Ben Rais Lasram *et al.*, 2010): (i) a high probability of immediate extinction (e.g. *Corcyrogobius liechtensteini* and *Didogobius schlieweni*), (ii) a high probability of extinction by the end of the 21st century after severe climatic niche reduction (e.g. *Gobius geniporus* (see Fig. 1), (iii) severe habitat fragmentation (e.g. *Arnoglossus kessleri* (Fig. 1) and (iv) migration to the coldest areas, associated with habitat reduction (e.g. *Cyclothone pygmaea*).
Among the winner species, 77% are predicted to experience high range extensions, reaching 80% or even 100% increase. This is for example the case of *Solea aegyptiaca* (Fig. 1) that is currently distributed along the southern and the eastern sides of the Mediterranean (from Tunisia to Turkey) as well as the Adriatic Sea and the Gulf of Lion. By the middle of the century, it could reach the Aegean Sea, the Tyrrhenian Sea and the Catalan coasts. Its distribution area projected using its climatic niche is expected to extend by 88%. By the end of the century, this species would be distributed in the whole Mediterranean except the extreme west of the Alboran Sea and an enclave in the northern part of the Aegean Sea (Ben Rais Lasram *et al.*, 2010).

Sea water warming would lead to a total modification of endemic species assemblages: as a whole, 25% of the Mediterranean Sea is predicted to experience a total modification of endemic species assemblages by the end of the 21st century. At that point, global warming would be so marked that none of the endemic fish assemblages of the Mediterranean would be identical to those of the 1980s.

According to climate envelope models projections, the Gulf of Gabes (southern Tunisia) together with the Levantine Basin and the southern side of the eastern basin would undergo the highest turnover rate in species composition i.e. close to 100% (Ben Rais Lasram *et al.*, 2010). That is, all endemic species in those areas would disappear (by extinction or migration) and be replaced by others.

Tunisia and the Gulf of Gabes in particular are actually under scrutiny in a context of global change and provide an interesting case study. Indeed, Tunisia lies at the transition between the warm

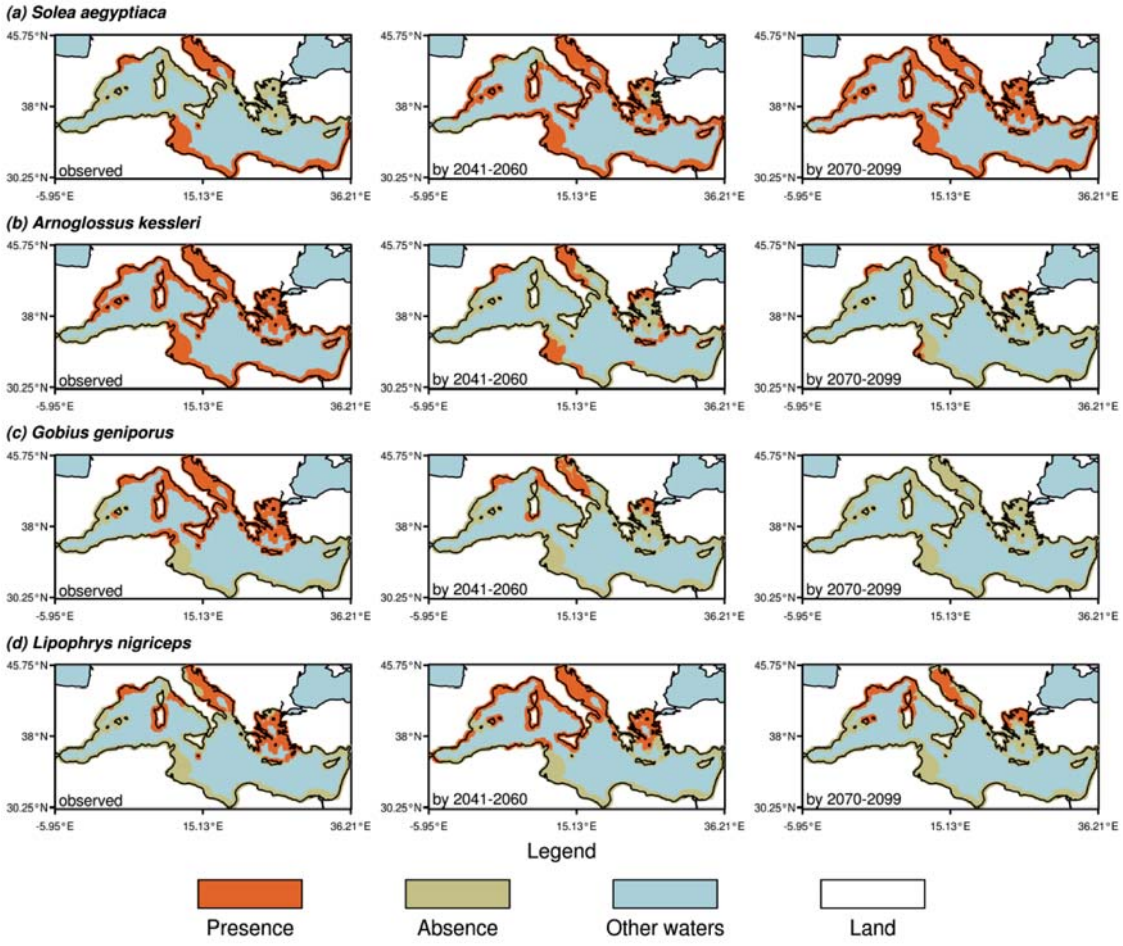

Fig. 1. Observed (1980s) and predicted (by 2040-2060; by 2070-2099) distribution areas of four endemic Mediterranean Sea fish species, and potential future thermal habitats projected with climate envelope models. The axes indicate degrees of latitude (X-axis) and longitude (Y-axis).

Levant basin and the cooler western part of the Mediterranean Sea and consequently exhibits both thermophilic and cold water species assemblages.

According to an updated inventory of the Tunisian ichthyofauna (Bradai *et al.*, 2004), 327 fish species inhabit the Tunisian coastal waters. The major part (86.24%) is of Atlantic origin, 7% are endemic species and nearly 2% are Lessepsian migrants. The latter are more frequent in the Gulf of Gabes where their frequency is increasing.

Considering the thermal affinities of the fish species present in Tunisia, 67% of them are temperate and thermophilic species and 14% are cold water species (Bradai *et al.*, 2004). In the Gulf of Gabes, we count nearly 73% of thermophilic species and 12% of cold water species.

It is now obvious that these assemblages are expected to undergo an intense reorganization due to species turnover induced by sea water warming.

Tunisian waters, as for the rest of the Mediterranean Sea, are experiencing the effects of global change: studies carried out on historical databases revealed positive trends in water temperature and salinity during the last century (Ben Mahmoud and Harzallah, 2009). The trends differ spatially: salinity increases in the southern Sicily Channel but decreases in the north; temperature increases particularly in the Atlantic water layer. These variations indicate a warming of the surface

layers and a more active thermohaline circulation with more entries of Atlantic water at the surface and more exits of Mediterranean water at the intermediate layers (Ben Mahmoud and Harzallah, 2009).

The ecological consequences of global change consist in the arrival of exotic species favored by the changing abiotic conditions: *Trachypenaeus curvirostris* and *Metapenaeus monoceros* (Missaoui and Zaouali, 1995), *Pisodonophis semicinctus, Parexocoetus mento, Seriola fasciata* and *Pempheris vanicolensis* (Bradai *et al.*, 2004), *Fistularia commersonii* and *Parexocoetus mento* (Ben Souissi *et al.*, 2004), *Cheilopogon furcatus* (Ben Souissi *et al.*, 2005) etc. and recently *Lagocephalus sceleratus* (Jribi and Bradai, 2012).

The Gulf of Gabes seems to be the most affected Tunisian ecosystem by global change. Indeed, in this area overfishing, pollution and introduction of exotic species operate in synergy and affect directly the structure and composition of species communities.

The Gulf of Gabes covers a continental shelf area of 35 909 km2 and is the second largest ecosystem in the Mediterranean Sea (the Adriatic Sea being the largest). The 200 m isobath is reached at 250 km off the shoreline. The ecological originality of the Gulf of Gabes (high diversity, *Posidonia* meadows) and the accessibility (very shallow slope of the continental shelf, soft bottoms) are suitable for bottom trawling and have contributed to a considerable increase in the number of fishing fleets. The Gulf of Gabes has become the main area in which fishing activity in Tunisia is concentrated.

The high biodiversity of the Gulf of Gabes, favored by the *Posidonia* meadows, is threatened by three factors: unsustainable fishing, pollution and global change resulting in an increasing number of exotic species.
First, irresponsible fishing, and particularly bottom trawling, causes a progressive but systematic destruction of *Posidonia* meadows. The regression of the meadows that give the Gulf of Gabes its reputation, has been reported in the literature since 1925 (Le Danois, 1925). Trawling has led to bare bottoms in many areas of the Gulf and some studies estimate that the fishing effort exceeds the optimum by 33% (Missaoui *et al.*, 2001).
Second, the Gulf of Gabes undergoes severe problems of pollution especially from the phosphate industry. Discards of chemical complexes led to the accumulation of a thick black deposit on a completely azoic surface. The combined effect of pollution and overfishing has resulted in large changes in the Gulf of Gabes ecosystem. Large areas of *Posidonia* have disappeared, *Cymodocea nodosa* is scarce and *Caulerpa prolifera* has almost completely disappeared. Regression of the vegetation cover by 90% led to biological communities characterized by flora and fauna of degraded environments (Ben Mustapha *et al.*, 1999).
Third, the Gulf of Gabes is being invaded by alien species as a consequence of global change: several species, mainly Indo-Pacific, have emerged, such as the bivalve *Pinctada radiata* currently abundant (Bradai, 2000), the shrimps *Metapenaeus monoceros* and *Trachypenaeus curvirostris* that strongly compete with the native shrimp *Penaeus kerathurus* (Missaoui and Zaouali, 1995), the green alga *Caulerpa racemosa* (Ben Alaya, 1971) and the Brachyura *Eucrates crenata* that became very abundant (Zaouali, 1992). There are about twelve exotic fish species including *Siganus luridus, Siganus Rivilatus, Parexocoetus mento, Seriola fasciata* and *Pisodonophis semicinctus.*

Projections derived from climatic envelope models and carried on endemic species (Ben Rais Lasram *et al.*, 2010), revealed that the Gulf of Gabes would undergo the highest turnover rate in the Mediterranean Sea with the loss of some species and the appearance of some others. Among the looser species we can cite *Ophidion rochei* and *Raja polystigma* that are expected to undergo a severe reduction of their thermal habitat in the Gulf of Gabes by 2070–2099. Conversely, *Didogobius bentuvii* and *Panturichthys fowleri*, that are both present at the extremity of the Levantine Basin, are projected to extend their thermal habitat and to reach the Gulf of Gabes by the end of the century.

Currently, excepting the case of the Lessepsian shrimps *Metapenaeus monoceros* and *Trachypenaeus curvirostris* that strongly compete with the native shrimp *Penaeus kerathurus* and are now commonly commercialized but with lower prices that *P. kerathurus*, there is no evidence

of competition nor extirpation of the Gulf of Gabes native species by exotic species. However, those species have to be under scrutiny because the biological consequences remain challenging to predict.

Endemic marine Mediterranean species are thus likely to undergo a biotic stress materialized by exotic species and an abiotic stress materialized by global warming. The former being favored by the latter, it is likely that both pressures add up and act in synergy leading to the increase of vulnerability of endemic species. This is even more critical in a highly impacted area such as the Gulf of Gabes where overfishing and pollution exacerbate the consequences of global change.

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* to be cited as:

Ben Rais Lasram F. 2013. The Gulf of Gabes, southern Tunisia: an endemic fish hotspot under threat pp. 129 - 133 *in* CIESM Workshop Monograph n°45 [F. Briand, ed.] Marine extinctions - patterns and processes, 188 p., CIESM Publisher, Monaco.