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Cumulative human threats on fish biodiversity components in Tunisian waters

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Abstract

Human activities are increasingly impacting biodiversity. To improve conservation planning measures in an ecosystem-based management context, we need to explore how the effects of these activities interact with different biodiversity components. In this study, we used a semi-quantitative method to assess the cumulative impacts of human activities on three biodiversity components (species richness, phylogenetic diversity, and functional diversity) in Tunisia's exclusive economic zone. For each of the nine activities considered, we developed an understanding of their effects from local studies and the expert opinion of stakeholders with country-specific experience. We mapped the cumulative effects and the three biodiversity components and then assessed the degree to which these elements overlapped using an overlap index. This is the first time such an assessment has been made for Tunisia's marine ecosystems and our assessment highlight the inappropriateness of current conservation measures. The results of this study have specific application for the prioritization of future management actions.

Keywords: Anthropogenic impacts, species richness, phylogenetic diversity, functional diversity, conservation planning.

Introduction

Biodiversity provides important ecosystem goods and services. Its role in supporting human well-being was formally recognized in December 1993with the signing of the Convention on Biological Diversity (Beaumont *et al.*, 2007; Cardinale *et al.*, 2012). Despite this awareness, however, biodiversity is more threatened today than ever before. Studies indicate that humans have altered nearly half the world's ecosystems (Barnosky *et al.*, 2011), and suggest moreover, that we have entered a new phase of mass extinction. The five preceding mass extinctions (occurring between the Cambrian and the Cretaceous) were all exclusively due to natural phenomena. However, this current event, called the "Holocene extinction", is being driven by both natural and human causes. Indeed, human activities are associated, directly and indirectly, with nearly every aspect of this event and the consensus is that it should be renamed the "Anthropocene mass extinction" (Wagler, 2011). It is also progressing at an unprecedented rate (Barnosky *et al.*, 2011).

Present day biodiversity, both marine and terrestrial, is deteriorating rapidly under the cumulative pressures of different human activities. It has been proven that human actions are dismantling ecosystems and eliminating genes, species, and biological traits (Cardinale *et al.*, 2012). Such disturbances may lead to biodiversity loss and changes to ecosystem functioning, consequences that will in turn have significant repercussions for society (Chapin *et al.*, 2000). Globally, human impacts can be summarized into four main categories: (1) over-exploitation of natural resources; (2) habitat modification, conversion, and fragmentation; (3) introduction of invasive species; and (4) pollution (Sponsel, 2001). In the marine realm, these threats are exacerbated by climate change and maritime traffic (Halpern *et al.*, 2008). In semi-enclosed ecosystems, such as the Mediterranean Sea, these activities can have an even more profound influence, especially on coastal environments (Coll *et al.*, 2010). Here, human activities and environmental conditions act together to influence the abundance and distribution of species (Navarro *et al*., 2015).

To reconcile the dual goals of biodiversity conservation and sustainable ecosystem use, it is necessary to promote new strategies of integrated management, for example, the ecosystem-based approach (EBM; Beaumont *et al.*, 2007). In EBM, knowledge of ecosystem processes is incorporated into management, with a view to balancing the delivery needs of all ecosystem services (Palumbi *et al.*, 2008). For example, in marine systems, multiple ecological mechanisms link the various biodiversity components and these links both support ecosystem function and provide a complex range of essential services (Palumbi *et al.*, 2008). Thus, preserving the different components of biodiversity may be broadly beneficial to a wide spectrum of important ecosystem processes and services. To achieve EBM goals it is necessary to understand how biodiversity interacts with human activities and their associated impacts. In the Mediterranean region, recent studies have focused on the cumulative impacts of human activities on species richness, habitats and ecosystems (e.g., Coll *et al.*, 2012; Micheli *et al.*, 2013; Navarro *et al.*, 2015), but to implement effective EBM, it is also essential to explore impacts on phylogenetic and functional diversities (PD and FD), among others.

Indeed, the loss of species with unique traits or those that belong to rare lineages may markedly affect ecosystem functioning (Cadotte *et al.*, 2008). Assessing impacts on FD can help identify species with a unique combination of traits that assist in ecosystem regulation (Norling *et al.*, 2007). It can also help identifying levels of trait dissimilarity within species assemblages, a factor which is known to be associated with increase rates of ecological processes (Mouillot *et al.*, 2011). Meanwhile, the amount of PD within an assemblage has been shown to explain ecosystem productivity (Cadotte *et al.*, 2008) and stability (Cadotte *et al.*, 2012). Therefore, knowing how and where PD and FD are being impacted by human activity is critical.

Cumulative impact assessments are generally carried out at the global or regional scale. Halpern *et al.* (2008) pioneered a standardized and quantitative method to assess the impacts of human activities on marine ecosystems at a global scale. In this study, global datasets on 17 different human stressors, ranging from fishing to commercial shipping and climate change, were used to assess 20 different marine ecosystems. Subsequently, this methodology was adopted by others to translate human activities into ecosystem specific impacts. For the Mediterranean Sea, areas of cumulative threats have been mapped with a view to assess their overlap with biodiversity hotspots (Coll *et al.*, 2012) and assist with the development of effective marine policy (Micheli *et al.*, 2013). While the results of these studies have been persuasive at coarse resolutions, they become less reliable at the local scale where pressure-impact relationships are very specific. Understanding these relationships, is vital for implementing locally-based management strategies and consequently, there is a need to move towards finer-scale analyses.

In Tunisia, biodiversity issues are playing an increasingly significant role across all areas of marine environmental policy. Stakeholders are seeking simple and easy approaches that can be immediately applied for conservation planning purposes. In this context, maps that show the overlap between human activities (and associated impacts) and biodiversity components would be useful. Such a product would have even greater relevance in Tunisia where to date, the establishment of marine protected areas (MPAs) has relied on classical diversity indices and has been influenced by factors such as the allocation of MPAs in military zones. In this study, we aimed to (*i*) map the cumulative impacts associated with human activities currently occurring in Tunisian waters and (*ii*) assess the degree of overlap between these impacts and different components of fish biodiversity, with an aim to improving future marine policy decisions.

Material and Methods

Study area

Tunisia is located in the southern Mediterranean, in the transition zone between the eastern and western basins (Fig. 1). Its coastline measures more than 1670 km in length and it is characterized by a variety of habitats. In the north, the seafloor is alternatively rocky and soft, with a narrow continental shelf, a steep slope and important biodiversity. The eastern region is less rocky and the continental shelf is wider. It features a number of similar species to the northern region, but with less biodiversity (Ben Mustapha & Afli, 2007). The southern region features the second widest section of continental shelf in the Mediterranean Sea and encompasses the Gulf of Gabes, one of the most productive ecosystems in the Mediterranean Sea, of great economic and ecological importance. The Gulf of Gabes supports extensive *Posidonia oceanica* meadows and high levels of fisheries (Hattab *et al.*, 2013). A review revealed that the northern region hosts 867 species, the eastern region hosts 292 species, and the southern region hosts 667 species (Afli, 2005), including all taxa. The study area encompasses 101,809 km^2, ranging from the coastline until the limit of the Tunisian Exclusive Economic Zone (EEZ) (Fig. 1).

Human threats: mapping and calculating cumulative impacts

In this study, we relied on the extensive experience of multiple experts to gain an understanding of nine human activities currently impacting Tunisia's marine biodiversity. These threats are artisanal fishing, industrial fishing, aquaculture, pollution, the extraction of hydrocarbons, shipping, invasive species, climate change, and habitat degradation.

Some fish species may be not directly affected by certain threats. But given that predator-prey interactions are governing communities structure and that composition of fish communities has great bearing on lower or higher trophic levels through top-down and bottom-up processes (Zambrano *et al.*, 2006), the whole fish diversity may be directly or indirectly affected by the human threats included in this study.

The following section briefly discusses each threat in more detail.

Fishing activity

The distinction between artisanal and industrial fishing is not standardized around the world. The Food and Agriculture Organization (Féral, 2001) identifies boats operating a short distance from shore as artisanal ves-

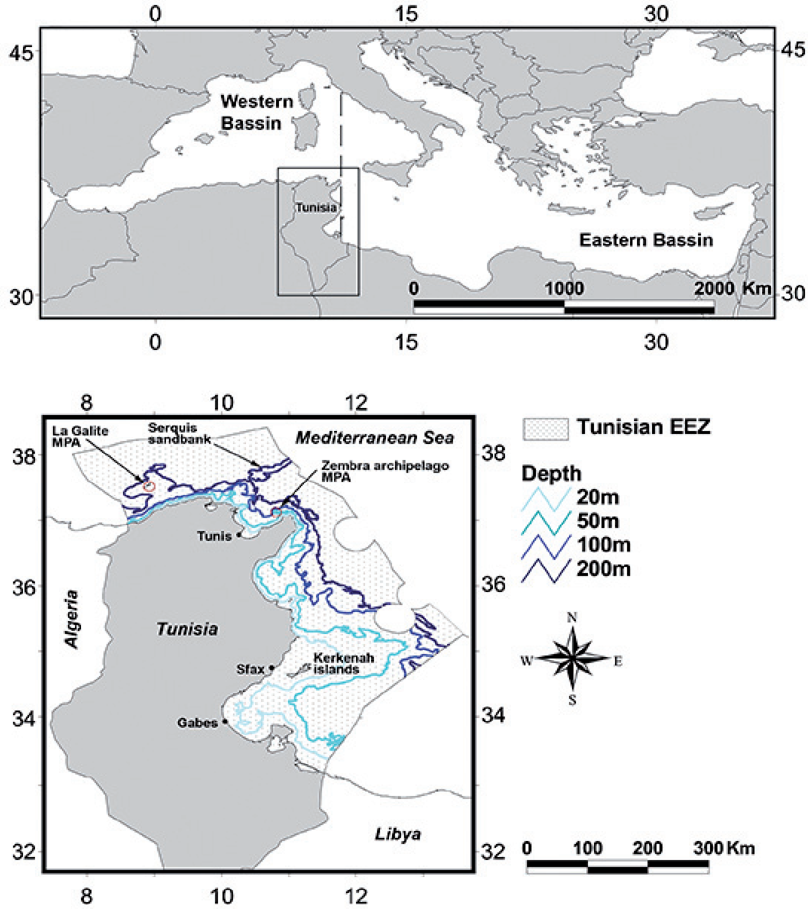

Fig. 1: Geographical location of the study area in the Mediterranean Sea and the main geographical features of Tunisia's exclusive economic zone.

sels, while their definition of an industrial vessel includes those with onboard processing facilities. Under the Tunisian Fisheries Department definitions, the only industrial fishing activity occurring in Tunisia is trawling, despite the fact that onboard processing does not actually occur on the majority of trawlers. The other vessels using a range of gear types (e.g., bottom and mid-water gillnets, pots, traps, longlines, purse seines and fishing with lights) are considered to be artisanal or coastal. The Tunisian coast hosts 43 fishing ports, each of which supports betweensevenand789 boats. Only nine ports support the industrial bottom trawling fleet (note that pelagic trawling does not currently occur in Tunisian waters), with vessel numbers ranging between one and238 boats per port. To estimate the fishing-related impacts associated with each port, we randomly selected a sample of fishermen in each of the main fishing ports and asked them to estimate their average fishing range.

We sampled 124 bottom trawling boats on the 5 main fishing ports among the 9 ports hosting trawlers. This corresponds to nearly 41% of the fleet of the chosen ports. For coastal fleet, we sampled 205 fishing boats on the 12 main fishing ports among the 43 ports hosting coastal or artisanal fishing activity. This corresponds to nearly 20% of the fleet of the chosen ports.

Using this information, we then created fishing pressure buffers to capture the fishing pressure exerted from each port.

Aquaculture

During the last 25 years, aquaculture has proliferated in Tunisia's coastal zone and it is becoming an increasingly important industry. Once considered an environmentally benign practice, fish farming is now viewed as a potential polluter (Pusceddu *et al.*, 2007). Significant research has been undertaken to examine the impacts of aquaculture on the environment, particularly water quality and disturbance effects on benthic communities. It has been shown that the release of organic matter associated with aquaculture activities causes changes in the composition of benthic communities (Karakassis *et al.*, 2000). The extent to which these disturbances extend beyond the farm boundaries appear varied, with reported distances ranging from 10 to 300m for Mediterranean based farms (Karakassis *et al.*, 2000; Klaoudatos *et al.*, 2006; Neofitou *et al.*, 2010). Aquaculture operations are also known to impact the behavior of wild fish as they assemble around the cages to take advantage of the discharge of food waste and feces (FAO, 2003).

There are 28 offshore aquaculture farms in Tunisia's EEZ (in waters <30 m), the majority of which are located on the country's eastern side. Coordinates for each farm were obtained from the Tunisian Fisheries and Aquaculture Department. As there was little country-specific data available on the impacts of these farms, we compiled information from a range of recent Mediterranean based studies (Karakassis *et al*., 2000; Klaoudatos *et al*., 2006; Neofitou *et al*., 2010). Using this information we developed a ranking system to categorize the level of impact, depending on its spatial extent: Impact3 (0 to 50m), Impact2 (50 to 150m), Impact1 (150 to 300m) and Impact 0 (>300m). Buffers of differing widths corresponding to the different impact levels were drawn around each farm.

Pollution

Most coastal areas around the world are reported as having incurred some pollution-related damage (Islam & Tanaka, 2004). The production and emission of pollutants are associated with a range of human activities, including the development and construction of infrastructure, agriculture, industrial development, and urbanization (Islam & Tanaka, 2004). To identify potential sources of pollution in our study site, we obtained a map from the Agence de Protection et d'Aménagement du Littoral (APAL; www.apal.net.tn), which presented all the database information on outfall locations along the Tunisian coast. These outfalls discharge a range of agricultural, industrial, and domestic wastes. Since the dispersal of pollutants depends on site-specific hydrodynamic conditions, we compiled the results of two previous impact studies carried out by APAL (APAL, 2009, 2015) and used this information to develop a ranking system to categorize the level of impact. As above, buffers of differing widths were drawn around the pollution source according to the following impact levels: Impact3 (0 to 300m), Impact 2 (300 to 2000m), Impact 1 (2000 to 9000m), and Impact 0(>9000m).

Offshore hydrocarbons activities

The offshore extraction of hydrocarbons (e.g., crude oil, liquefied natural gas) is potentially a major hazard for the marine environment. Offshore installations can disturb benthic organisms during their placement and functioning, and oil discharges can have significant deleterious impacts. The most widespread and dangerous consequence associated with the oil and gas industry, however, is pollution thatcan occur in conjunction with all activities undertaken at every stage of production, from exploration to refinement (Kharaka & Dorsey, 2005).

The threat related to offshore hydrocarbons activities affects directly benthic communities. Since there is a strong control exerted by benthic communities on upper trophic levels such as fish (Hattab *et al*., 2013), one can consequently assume that perturbations on benthic communities can easily impact fish diversity.

Ten offshore concessions currently operate in Tunisia's EEZ, each with one or more wells. There are also four coastal oil refineries and a pipeline network, which serves the largest concessions. We collected data on these infrastructures from the online Entreprise Tunisienne des Activités Pétrolières database (www.etap.com.tn). As with the two preceding threats, we developed a ranking systembased on the spatial extent of environmental disturbances. The categories defined were Impact3 (0 to 500m from the well(s) and/or refineries), Impact2 (500 to 1000m from the well(s) and/or refineries), Impact1 (inside the concessions; 0 to 100m around the pipelines) and Impact 0 (elsewhere). Buffers of differing widths corresponding to the different impact levels were drawn around each component of hydrocarbon.

Shipping

Shipping is recognized as having adverse impacts on marine habitats and species: these impacts can result from the associated pollution (e.g., related emissions of petroleum hydrocarbons, antifouling, biocides, and litter), noise, the introduction of invasive species, disturbances to soft sediment bottoms during navigation, and physical damages (e.g., propeller scarring, anchoring, and groundings; Abdulla, 2008). As commercial shipping data for Tunisian waters was not available, we used global-scale data collected by Halpern *et al.* (2008).

Invasive species

At a global scale, invasive species are recognized as a major threat to biodiversity (Davis, 2003). There is now sufficient evidence to show that invasive species can 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 the structure and energy flows of food webs (Libralato *et al*., 2002). Further, species can be driven to extinction by competitive interactions with invasive species (e.g., Olden *et al*., 2006), predation by invasive species (e.g., Roemer *et al*., 2002), or simply by demographic stochasticity when large numbers of new individuals enter the community and occupy part of the carrying capacity (Lande, 1993). The Mediterranean Sea has the highest number of exotic species of anywhere in the world (Streftaris *et al*., 2005), with the Suez Canal and Gibraltar Strait acting as two key pathways for their introduction. Along the Tunisian coast, 20 Lessepsian fish species and 14 fish species of Atlantic origin have been identified (CIESM, 2015). Using information sourced from the atlas and grey literature of the Commission Internationale pour l'Exploration Scientifique de la Méditerranée (CIESM), we created a database of the geographical ranges of all known exotic fish species along the Tunisian coast. This information was then used to map species richness values in a Geographical Information System (GIS).

Climate change

There is now considerable evidence to illustrate the ecological impacts of climate change on marine ecosystems (e.g., Jones *et al*., 2013; Woodworth-Jefcoats *et al*., 2013; Engelhard *et al*., 2014). Like the rest of the world, the Mediterranean Sea is becoming warmer. For the last 30 to 40 years, sea temperatures have been rising at the surface and at depth (Rivetti *et al.*, 2014). According to the regional climate model NEMOMED8, sea surface temperatures (SST) in the Mediterranean Sea are expected to keep warming, with an estimated increase of 2.8°C forecasted by the end of the 21stcentury (Beuvier *et al*., 2010). Along the Tunisian coasts and according to NEMOMED8 model, temperatures are projected to increase by 2.4° to 2.8°C by 2080-2099.

In this study, we calculated the average rate of change in SST values during the hottest month of the year (i.e., September; 1982-2012) as a proxy measure of current climate change. To perform this calculation, we used data derived from the multisatellite Pathfinder V5.2 Advanced Very High Resolution Radiometer (AVHRR) SST dataset processed to a resolution of approximately 4.6 km at the equator (http://data.nodc.noaa.gov/pathfinder/Version5.2/). These data have the highest resolution and cover the longest time period of any satellite-based ocean temperature dataset (Casey *et al*., 2010). All the day and night Pathfinder SST daily fields were loaded into an R environment to calculate monthly mean maps for each September in the considered time period. The long-term monthly mean SST fields were then used to calculate the slope of SST in each grid cell using linear regression.

Habitat degradation

Habitat degradation is one of the major drivers of global environmental change, responsible for local extinctions and declining ecosystem services (Wilson *et al*., 2008). In the Mediterranean Sea, studies have demonstrated that habitat degradation is the second most important human impact, the first being overexploitation (e.g., Coll *et al.*, 2010). In Tunisian waters, critical habitats include the *Posidonia* seagrass meadows, the coralligenous assemblages, and the vermetid reefs built by *Dendropoma petraeum* (Ben Mustapha & Afli, 2007). As the results of existing habitat assessment studies are patchy, we used expert knowledge to rank levels of habitat degradation using a 0 to 3 scale.

The impact zones of each of the nine threats were summarized at a 0.1° grid resolution (a total of 1986 cells). The human impacts were mapped using GIS (QGIS 2.6.1). Following Halpern *et al.* (2008), we then assigned a weighting score to each threat layer: a similar approach was also used by Coll *et al.* (2012) and Micheli *et al*. (2013). A group of external experts (and this study's co-authors) were then asked, using a questionnaire, to rank each threat from 0 to 5, according to their expert knowledge and taking into account the relative importance of each threat to biodiversity. We relied on the knowledge experience of 14 experts. Two of them come from Mediterranean countries and 12 are Tunisians experts. Among these latter, 6 belong to research institutes and 6 to universities. Five of them have proven consulting experience on environmental impact studies with ministries.

We then log[X+1] transformed these values and rescaled them between 0 and 1 to enable direct comparisons. Finally, we calculated a threat index (T_i) for each grid cell following:

$$T_i = \sum_{i=1}^{n} w_i \times v_i$$

where *i* is the layer number, n is the total number of layers (nine), w_i is the weight of layer *i*, andv_i is the threat value for layer *i*.

Biodiversity components mapping

Species data and species richness

For the study site, we extracted presence-absence data for 438 fish species from the FishMed database (Albouy *et al*., 2015): this database compiles geographical distribution information for fish species published in the Fishes of the Northern Atlantic and Mediterranean (FNAM) atlas (Whitehead et al., 1986). Currently, this atlas provides the only available basin-wide occurrence information for all Mediterranean fish species. The occurrence maps generated for each species were refined by removing areas whose depths fell outside their known depth range (see Albouy *et al*. (2015) for more details about the database). Thus, our final dataset summarized the occurrence of 438 fish species within the Tunisian EEZ at a 0.1° grid resolution. The species richness of each cell was obtained by summing each row in the presence-absence matrix.

Phylogenetic and functional diversity of fish assemblages

In this study, we used a phylogeny that included 62% of Mediterranean teleost fish species and nine outgroups (to build a dated phylogeny). This phylogeny was built from a DNA super matrix composed of four mitochondrial genes (12S ribosomal DNA, 16S ribosomal DNA, cytochrome c oxidase subunit I, and cytochrome) and two nuclear genes (rhodopsin and recombination activating gene I). This phylogenetic tree does not include all 438species present in our species dataset. Accordingly, the phylogenetic tree was pruned and 341 species were extracted (Meynard *et al*., 2012). For each fish assemblage, we computed its phylogenetic diversity using the PD index (Faith, 1992). The PD index relies on the amount of evolutionary history (based on branch length in a phylogenetic tree) represented by a set of species. To calculate functional diversity, we used the FishMed database to compile information on 10 traits for each of the 341fish species (present in the phylogentic tree): maximum length, vertical distribution range, preferred habitat types (e.g., rocky, soft bottom, or *Posidonia* seagrass meadows), the timing of migration and reproduction events, whether semelparity and/or sex shifts occur, larvae type, behaviour (e.g., gregarious *vs*. solitary or both), and diet (fishbase.org; Froese & Pauly, 2014). We quantified FD by computing the functional richness index (FRic; Villéger *et al*., 2008) based on Gower's method, which calculates the distance between each pair of species. This approach allows for variables of different natures to be mixed while giving them equal weight (Legendre & Legendre, 1998). We then performed a Principal Coordinates Analysis (PCoA) on Gower's distance matrix to identify the position of each species in the multidimensional functional space (see Buisson *et al*., 2013). We kept the first four principal axes of the PCoA to build a multidimensional functional space (Mouillot *et al*., 2013). The FRic index represents the volume of the functional space occupied by a given community. We calculated a biodiversity index (*Bi*) for each grid cell by summing the three biodiversity layers (i.e., species richness, functional richness, and phylogenetic richness), log[X+1] transforming the values and then rescaling them between 0 and1.This biodiversity index (*Bi*) lead to the drawing of a cumulative biodiversity map.

Overlap between the cumulative impacts of human activities and the biodiversity components

For each grid cell, the spatial congruence between the three biodiversity components and the cumulative impacts of the nine human activities were assessed using an overlap index (O_i) for each cell, calculated as:

$$Oi = Bi \times Ti$$

Results

Biodiversity component patterns

Species richness values exhibited both an inshore-offshore and latitudinal (south to north) gradient (Fig. 2a). Species richness was higher along the northern coast than the southern coast. Moreover, the coastal areas supported more fish species than the offshore areas, with the exception of the waters around the Kerkenah Islands, which featured the lowest species richness values in the broader Gulf of Gabes. Along the northern coast, some offshore areas also exhibited high species richness (e g., La Galite Island and Serquis Sandbank). Areas of lower species richness (i.e., <100 fish species per cell) were observed at the margins of the EEZ while hotspot areas, with up to 300 fish species per cell, appeared along the northern coast. PD and FD exhibited almost the same pattern (Fig. 2b and 2c). As with species richness, low PD or FD areas were located at the EEZ margins, while high diversity areas were encountered along the northern coast. In general, hotspots of all three biodiversity components matched well spatially. Finally, the cumulative biodiversity map also displayed a similar pattern (Fig. 3).

Threat patterns

Trawl fishing was most intense at depths of 50m or more, with up to 240 vessels operating in some grid cells. In the northern region, fishing intensity covered a greater area but was less important in terms of overall effort (Fig. 4a). Coastal fisheries activities were most intense in the coastal areas of the Gulf of Gabes (Fig. 4b) where the number of boats per cell reached a maximum of 5480. Aquaculture-associated pressures were restricted to the areas immediately surrounding the offshore farms and only affected 2% of the total study area (Fig. 4c). Pollution impacts were exclusively coastal (~20% of the total study area) and no associated impacts were identified beyond 15km offshore (Fig.4d). Offshore hydrocarbon extraction activities were limited to areas in the vicinity of the installations and collectively identified as impactingapproximately10% of the study area (Fig. 4e). Shipping pressure was most pronounced in the northern areas, with high impact regions representing 10% of the total study

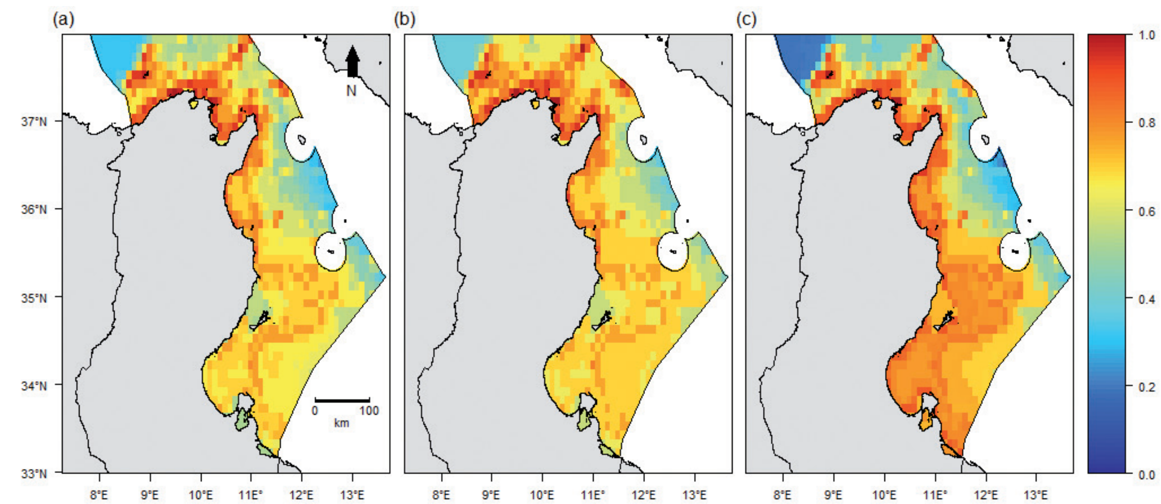

Fig. 2: The biodiversity components in the Tunisian exclusive economic zone [expressed on a log scale (0-1)]: species richness (a), phylogenetic diversity (b), and functional diversity (c).

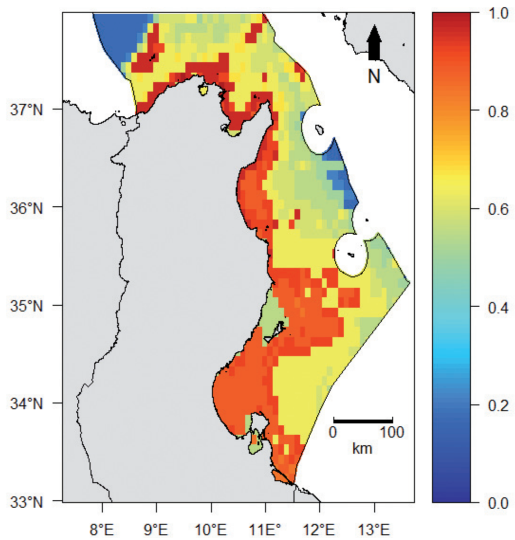

Fig. 3: The cumulative biodiversity components in the Tunisian exclusive economic zone [expressed on a log scale (0-1)].

area (Fig. 4f). Invasive species richness was relatively patchy, but in general, coastal areas were more colonized than offshore areas (Fig. 4g). The maximum number of invasive fish species recorded per cell was16. Climate change impacts were more pronounced in coastal areas and also showed a decreasing trend from south to north. Climate change impacts were found to be highest in the Gulf of Gabes (21% of the total study area; Fig. 4h). Habitat degradation was determined to be impacting 21% of the total study area, with most affected regions occurring in the Gulf of Gabes and the Gulf of Tunis (Fig. 4i). As expected, cumulative impacts were highest in coastal areas, with highly impacted regions accounting for 38% of the total study area (Fig. 5).

The experts assigned the highest weighting to trawling and habitat degradation, followed by pollution, climate change, coastal fishing, and invasive species. Activities associated with the offshore extraction of hydrocar-

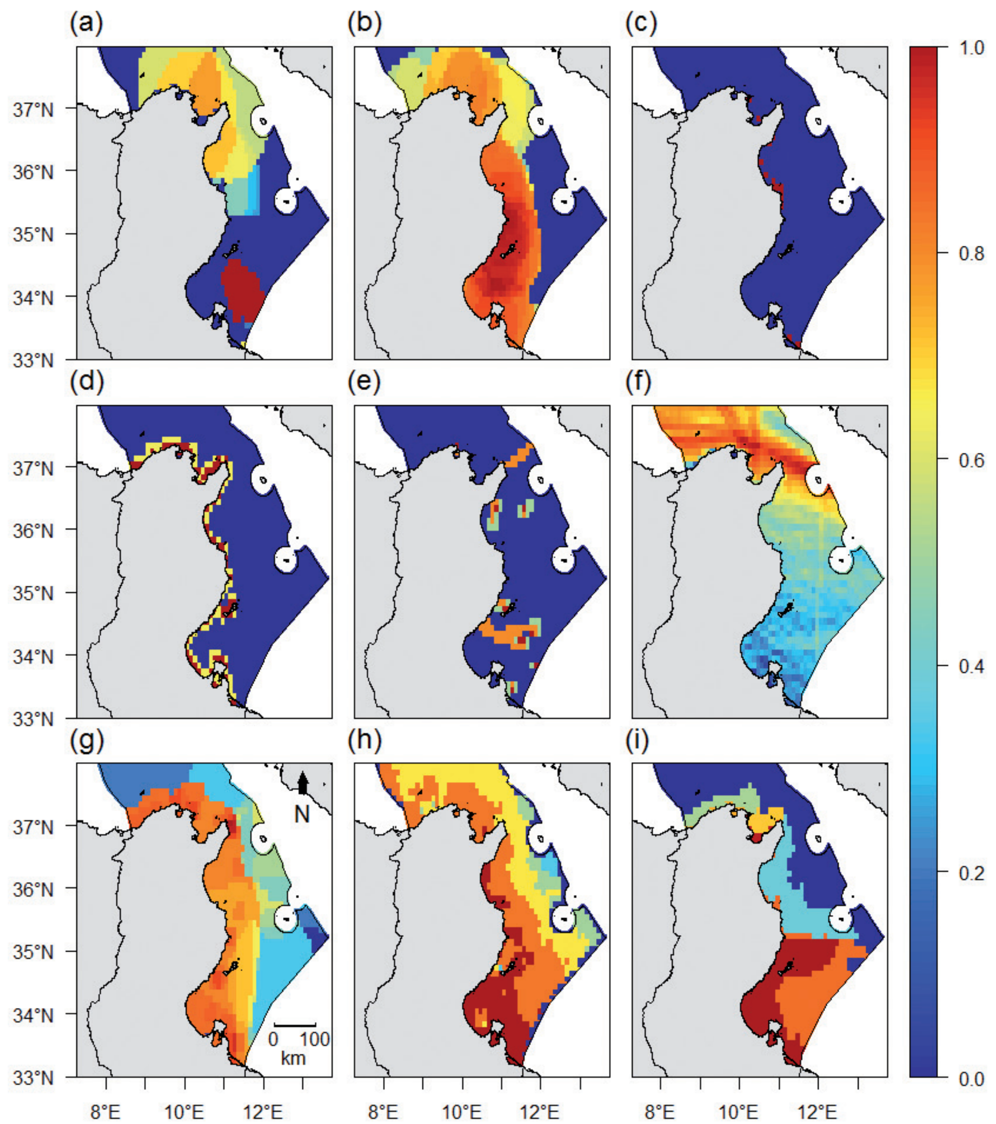

Fig. 4: Human threats in the Tunisian exclusive economic zone [expressed on a log scale (0-1)]: (a) Trawling, (b) Coastal fishing, (c) Aquaculture, (d) Pollution, (e) Offshore hydrocarbons activities, (f) Shipping, (g) Invasive species, (h) Climate change, and (i) Habitat degradation.

bons were estimated as having one of the lowest impacts, along with shipping and aquaculture (Fig. 6).

Overlap between the cumulative human threat and biodiversity components

Results indicate that there was a very low overlap (O_i≤25%) between the cumulative threats associated with human activities and the three biodiversity components in less than 1% of the study site (Tunisian EEZ). In approximately 15% of the study area, there was a low overlap (25%≤O_i<50%); in 35% of the area, there was a medium overlap (50%≤O_i<75%); and in 48% of the area, there was a high overlap (75%≤O_i<95%). Finally, there was a very high overlap (O_i≥95%) in 1.5% of the area: these high overlap areas occurred in the center of the Gulf of Gabes and in the Gulf of Tunis, particularly the Zembra Archipelago MPA (Fig. 7a). When the overlap with each biodiversity component was considered separately, the overlap patterns for both species richness

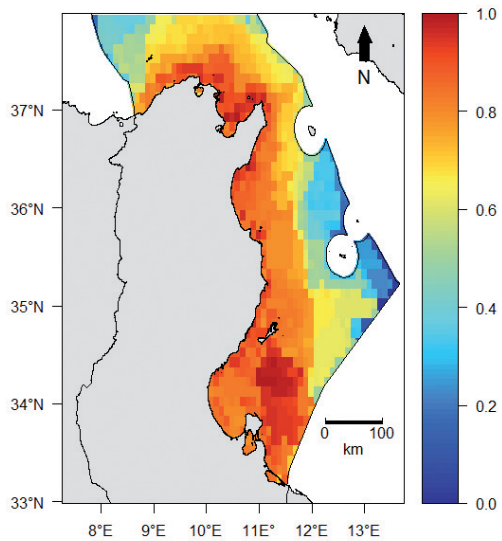

Fig. 5: Cumulative human threats in the Tunisian exclusive economic zone [expressed on a log scale (0-1)].

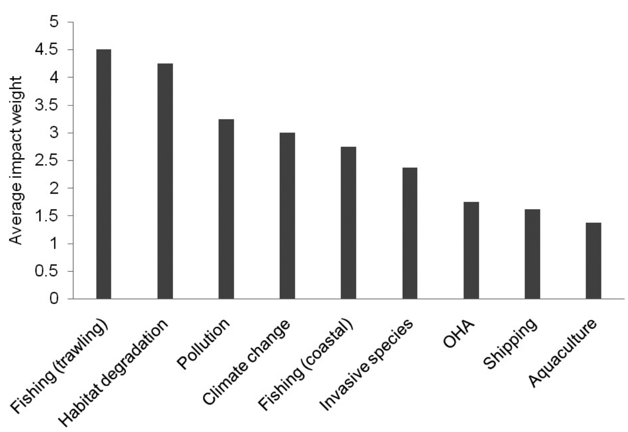

Fig. 6: Average impact weight of human threats. (OHA: offshore hydrocarbons activities).

and PD appeared very similar (Fig. 7b and 7c), while the overlap with FD was spatially less extensive. However, with FD areas of very high overlap were more prevalent (4.6% of the total area; Fig. 7c).

Discussion

A key component for conservation planning and management is understanding the intersect between biodiversity and human activities: by mapping these two elements, the degree of overlap (or zone of potential impact) can be easily identified. The results of such an approach could be incorporated within a transparent and repeatable structured decision-making (SDM) process and provide a useful tool for stakeholders (Tulloch *et al.*, 2015).

In this study, we used a semi-quantitative method to assess the cumulative impacts of human activities on three biodiversity components (species richness, phylogenetic diversity, and functional diversity) at a local scale. To complete this assessment, we compiled datasets for each of the nine human activities considered. We also drew heavily on the collective expertise and experiences of a range of stakeholders. Our study was inspired by the methodological approaches developed in previous global (Halpern *et al.*, 2008) and regional (Coll *et al.*, 2012; Micheli *et al.*, 2013) studies. Our analysis, however, was focused at the local scale and when assessing impacts, we broadened the scope to consider three distinct biodiversity components.

Biodiversity is more than just species richness. Rather, it can be viewed from alternative angles, using simple metrics that integrate biological differences between species that are related, either through evolution or by their functional traits. Such differences have been found to be important drivers of ecosystem functioning (Cadotte *et al.*, 2008, 2012): for example, evolutionarily diverse assemblages enhance ecosystem productivity (Cadotte, 2013). In another example, it has been found that maintaining stability in multiple ecosystem processes over long time periods and through multiple environmental change scenarios requires species with complementary functions (Isbell *et al.*, 2011). In cases where these three distinct biodiversity components are not spatially congruent, conservation actions that only focus on maintaining species richness may not adequately protect either the evolutionary history and/or functional diversity, with significant repercussions for the long-term viability of the ecosystem (Cadotte *et al.*, 2011). In the Tunisian context, all three components are more or less similarly distributed in space, which means that even if species richness is the sole focus of management efforts, those efforts are likely to preserve all biodiversity components. This could facilitate the implementation of conservation measures.

Despite global-scale data on human activities and their associated impacts becoming increasingly abundant and accessible through the work of organizations and

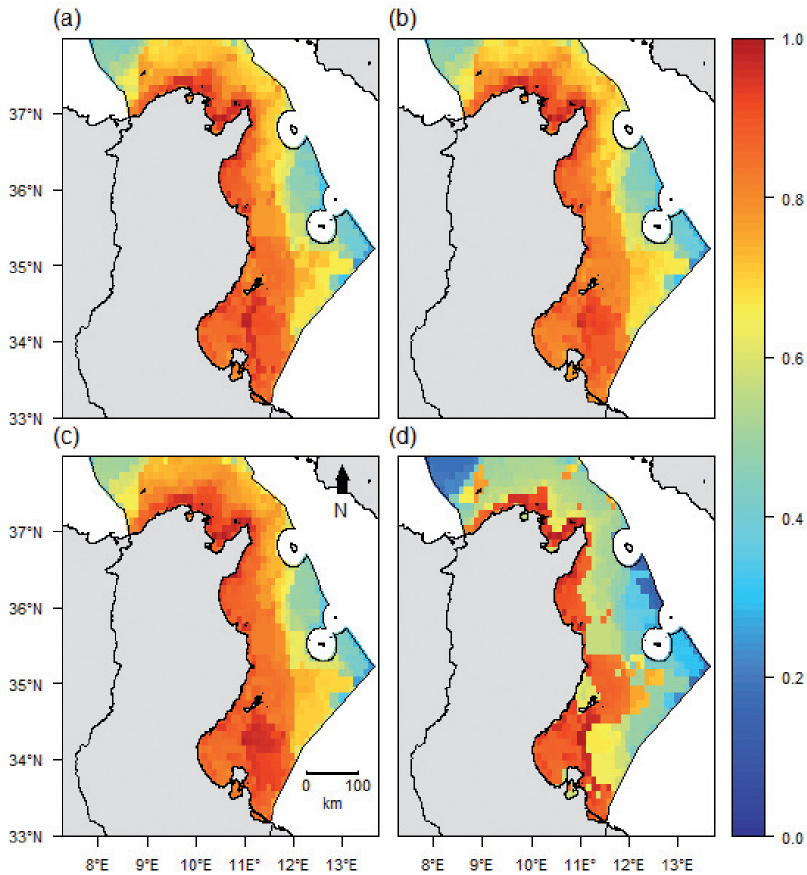

Fig. 7: Overlap values between cumulative human impacts and (a) cumulative biodiversity components, (b) species richness, (c) phylogenetic diversity, and (d) functional diversity.

initiatives such as the Sea Around Us Project, the National Oceanic and Atmospheric Administration, and the European Environmental Agency, at the local scale such information is not always available. In Tunisia, for example, despite the efforts of authorities to encourage data sharing and transparency, some data remain largely inaccessible. The results of this study indicate that the highest concentrations of both cumulative threats and biodiversity tended to be concentrated in coastal areas: the most highly impacted regions identified were located off the Gulf of Gabes and patches of the Gulf of Tunis. These areas correspond with those found by Micheli *et al*. (2013) and overall, the general overlap pattern is roughly similar to that found by Coll *et al.* (2012).

Our results also highlighted areas of 'high to very high' overlap around the MPAs in the La Galite and Zembra archipelagoes. At Zembra, an overlap value of close to 1was driven by very high threat and biodiversity indices while La Galite's overlap value of around 0.76 was due to a very high biodiversity index and a high threat index. Under Tunisian legislation, MPAs are further supported with an additional 1.5 nautical mile no-take zone. This measure seeks to reduce fishing-related pressures in neighboring areas but as our results highlight, it is also important to recognize the cumulative impact of all human activities. Further, current MPAs only cover a very small proportion of the high overlap areas identified, highlighting the need to extend Tunisia's MPA network and carefully monitor existing MPAs.

Being complementary with an hotspot approach (Roberts *et al.*, 2003), our analysis taking into account the overlap between cumulative threats and biodiversity, sets the basis for systematic conservation planning. Indeed, while evaluating the degree of overlap between threats and biodiversity in protected areas provides insights for their monitoring, further analyses are required to set cost-effective conservation solutions (Margules & Pressey, 2000). Such approaches, coined as systematic conservation planning (SCP), encapsulate the concepts and the tools needed to meet the basic objectives of reserve systems (representativeness of the different facets of biodiversity to be protected; and long-term persistence of species populations inside a network of protected areas), while minimizing cost and maximizing feasibility by providing flexible conservation solutions (Margules & Pressey, 2000). The data gathered here regarding protected areas location, biodiversity features, human induced threats and opportunity cost (fishing), constitute the basic bricks of SCP and provide the starting point for an affective SCP on Tunisian coasts.

Our approach could be modified to take into account other valuable biodiversity metrics such as beta diversity. This may be highly beneficial, as beta diversity has been proven to offer greater accuracy in a conservation planning context than either alpha or gamma diversity (Ferrier *et al.*, 2007).

Such an approach can also be used to improve our management of human activities, allowing us to target those having the most impact and thus, act to reduce the cumulative threat in biodiversity hotspot areas (Micheli *et al*., 2013). According to expert opinion, the three human activities with the highest impact in Tunisia are bottom trawling, habitat degradation, and pollution. These threats could be addressed through a reduction in fishing effort, improved outfall management and adequate habitat restoration measures, respectively. Climate change, coastal fishing, and invasive species are the next three highest impacting activities. Coastal fishing could be better managed through fisheries effort adjustments, and while the effects of climate change and invasive species cannot be removed, their impacts can be lessened through adaptation and mitigation measures (Micheli *et al*., 2013). Counter intuitively, offshore hydrocarbon extraction activities are considered to have some of the lowest impacts, despite the significant environmental risks an associated accident may bring. However, the drastic security measures taken to reduce the risk of accidents mean that we can consider their impact relatively low.

Our analyses have some limitations. Firstly, we did not consider the threat of illegal fishing, as data on this activity are scarce in Tunisia and the small amount of data that do exist are confidential. However, we know that trawlers make regular incursions into prohibited depths (DGPA, 2012), and illegal fishing gear types are used, especially a small trawl deployed by small boats in very shallow areas (<10m depth). This non-selective and highly destructive gear type results in the degradation of *Posidonia* meadows and the depletion of resource stocks (CGPM, 2000).

Secondly, due to the approach we used to quantify fishing effort, it is likely that fishing intensity was overestimated. Identifying the true boundaries of fishing zones is difficult because fishers are reluctant to reveal their fishing strategies. Consequently, instead of using maps of nominal or effective fishing effort deployed in real fishing zones, we used a procedure based on the estimation of the mean fishing range of each fleet. This results in potential fishing zones where fishing effort could be overestimated. The best way to overcome this limitation would be to use Vessel Monitoring System data, but this technology is not compulsory in Tunisia and to date, very few trawlers have allowed a system to be installed.

Thirdly, all fish species were affected by the same values of threat even if they are nor equally impacted by this threat (for example a goby is not as impacted by fishing as a swordfish and a swordfish is not as impacted by coastal pollution as a goby). One solution would be to weight each species by its sensitivity to a given threat.

Fourthly, the buffers representing the spatial extent of environmental disturbances around aquaculture farms and pollution outfalls were based on information compiled from a range of studies, each of which reported different results. Since the true spatial extent of environmental disturbance around each feature depends on the specific hydrodynamic and climate conditions found in each area, these homogenized impact scores that we assigned to each buffer category may be biased. Nevertheless, given the absence of studies investigating the each disturbance source, such a bias was unavoidable.

Finally, our threat index is based on weighting scores that were assigned for each threat layer. These weights were developed on contributions from experts with an extensive knowledge of Tunisia. The type of uncertainties related to such an approach have already been discussed in previous studies (e.g., Halpern *et al.*, 2008; Teck *et al*., 2010; Ramirez-Llodra *et al*., 2011; Micheli *et al*., 2013). Although quite subjective, this approach has nonetheless been proven to be robust and in this context, constitutes the best method at this scale for quantifying human impacts. Moreover, since we only used the opinions of those with country-specific expertise, it is valid to assume the outcome is semi-quantitative and realistic.

Despite these limitations, however, our study marks the first attempt to assess the overlap between human impacts and three different fish biodiversity components at a local scale. Our results revealed that such a simple spatial approach can be useful in environmental decision-making and for identifying conservation priorities when combined with systematic planning approaches. Access to improved data (i.e., type, quality, and quantity) would no doubt serve to enhance this analysis; however, in the interim, it establishes a useful foundation for improved conservation planning and should offer policy makers interesting opportunities. We recommend that future efforts should focus on exploring biodiversity changes under different climate change, invasive species, and management scenarios, undertaking sensitivity analysis to explore the effects of weights on final cumulative threats, and broadening the analysis to include all taxa.

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