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مبادرة أبوظبي العالمية للبيانات البيئية
Abu Dhabi Global Environmental Data Initiative

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AGEDI | THE ABU DHABI GLOBAL ENVIRONMENTAL DATA INITIATIVE

CLIMATE CHANGE PROGRAMME

Marine Biodiversity Vulnerability to Climate Change

- Atmospheric Modelling
- Arabian Gulf Modelling
- Terrestrial Ecosystems
- Marine Ecosystems
- Transboundary Groundwater
- Water Resource Management
- Al Ain Water Resources
- Coastal Vulnerability Index
- Desalinated Water Supply
- Food Security
- Public Health Benefits of GHG Mitigation
- Sea Level Rise

Full Technical Report

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Abu Dhabi Global Environmental Data Initiative

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About this Final Technical Report

In October 2013, the Abu Dhabi Global Environmental Data Initiative (AGEDI) launched the "Local, National, and Regional Climate Change (LNRCC) Programme to build upon, expand, and deepen understanding of vulnerability to the impacts of climate change as well as to identify practical adaptive responses at local (Abu Dhabi), national (UAE), and regional (Arabian Peninsula) levels. The design of the Programme was stakeholder---driven, incorporating the perspectives of over 100 local, national, and regional stakeholders in shaping 12 research studies across 5 strategic themes.[1] The "Marine Biodiversity and Climate Change" study within this Programme aims to assess the potential impacts and the vulnerability of marine biodiversity and fisheries in the Arabian Gulf to climate change.

The purpose of this "Final Technical Report" is to offer a comprehensive discussion of what has been learned in carrying out the research activities involved in the "Marine Biodiversity and Climate Change" study. Over a series of webinars, all comments raised by stakeholders on a previous draft of the results have been discussed and this Final Technical Report incorporates responses to that feedback in form of updates to the analytical results, additional technical details, and recommendations for future work. In short, this report seeks to provide the reader with a comprehensive overview of the results of the assessment, supported by a discussion of the input data, methodology, modelling tools and other issues that can support future research and policymaking regarding the marine conservation planning under climate change.

[1] For more information on the LNRCC programme and the marine biodiversity sub-project, please contact Jane Glavan (lnrclimatechange@ead.ae).

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List of Acronyms

AGEDI	Abu Dhabi Global Environmental Data Initiative
AR	Assessment Report (of the IPCC)
BIOCLIM	Bioclimate analysis and prediction model
EAD	Environment Agency of Abu Dhabi
EEZ	Economic Exclusive Zone
ENFA	Ecological Niche Factor Analysis
FAO	Food and Agriculture Organization of the United Nations
GCC	Gulf Cooperation Council
GCM	Global Circulation Models
GHG	Greenhouse gas
HBS	Habitat Biodiversity Suitability
ILO	International Labour Organisation
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for the Conservation of Nature
km	kilometer
LNRCCP	Local, National, and Regional Climate change Programme
MPA	Marine Protected Area
NPPEN	Non-Parametric Probabilistic Ecological Niche model
psu	Practical salinity units
RCP	Representative Concentration Pathway
RECOFI	Regional Commission for Fisheries
ROPME	Regional Organization for the Protection of the Marine Environment
SST	Sea surface temperature
UAE	United Arab Emirates
UN	United Nations
UNDP	United Nations Development Programme
UNEP-WCMC	United Nations Environment Programme World Conservation Monitoring Centre
UNCLOS	United Nations Convention on the Law of the Sea
WHO	World Health Organisation

Selected Glossary

Phenology	The study of cyclical, including seasonal natural phenomena, particularly as they relate to climate (e.g., bird migration, plant blossoming).
Habitat suitability	Degree to which given attributes that define an animal or a plant's environment (e.g., temperature and salinity) fall within a species' observed range.
Ecosystem services	Benefits primarily human beings derive from natural systems. The Millennium Ecosystem Assessment[2] grouped these services into four categories: *provisioning*, such as the production of food; *regulating*, such as the control of climate; *supporting*, such as nutrient cycles; and *cultural*, such as recreational benefits.
Benthic	Related to, or associated with, the bottom of a body of water, here the ocean.
Spline interpolation method	A mathematical means of calculating new data points within the range of known data points using a special type of non-parametric piecewise polynomial regression called a spline.
Subsistence catch	Fish, invertebrates and other seafood caught primarily to feed a fisher's family and relatives.
Commercial catch	Fish, invertebrates and other seafood caught with the intent of being sold (i.e., for the purposes of making profits).

[2] Millennium Ecosystem Assessment (MA) 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington. 155pp.

Executive Summary

This study aims to **provide an assessment of the potential impacts to, and the vulnerability of, marine biodiversity and fisheries in the Arabian Gulf as a result of climate change**. Climate change is expected to affect the ocean properties of the Arabian Gulf. These changes, including significant warming, a shift in salinity and current patterns, and sea level rise, are expected to impact marine organisms and the fisheries that are exploiting some of these species.

Firstly, we assessed the current status and trends for biodiversity and fisheries in the Arabian Gulf. Secondly, we applied simulation modelling approaches to assess the impacts to, and vulnerability of, marine biodiversity, including charismatic and non-fish species, to climate change. Thirdly, we conducted a vulnerability assessment of national economies to climate change impacts on fisheries. Finally, we discuss the implications of these impacts for conservation and fisheries management policies in the region.

We collated data for almost 1,400 marine species occurring in the Arabian Gulf. Details for these species are available online through FishBase (Arabian Gulf ecosystem fish list here) and SeaLifeBase (non-fish list here). Records included 817 fish species (0.5% recorded endemics), 39 marine chordates other than fish (46% seabirds, 23% marine mammals, 13% sea turtles, 8% sea snakes, 10% other chordates), 480 invertebrates (so far, 5% endemics, all of which are annelid worms; 47% annelids, 26% molluscs, 19% arthropods, 9% cnidarians, 2% echinoderms, cyanobacteria and acanthocephalians), and 35 marine plant species (34% brown algae, 31% green algae, 23% red algae and 11% vascular plants). Amongst the Arabian Gulf species, 335 species are Red Listed by the International Union for the Conservation of Nature; 50% are bony fishes, 22% sharks and rays, 12% anthozoans, 5% seabirds, 4% cephalopod molluscs and the rest are marine mammals, sea snakes, sea turtles, crustaceans and bivalve molluscs. These records will need to be evaluated on a species-specific basis by local experts and requests for deletions/substitutions submitted to Fishbase/SeaLifebase, with supporting information, so that species' status can be revised and corrections made where appropriate.

Overall, reconstructed catches of the Arabian Gulf show an increase from 1950 to 2000 from 200,000 tonnes to around 600,000 tonnes per year, followed by a decline to about 400,000 tonnes per year in the 2000s. Our results suggest that all countries in the Gulf under-report their catches, with the exception of the United Arab Emirates (UAE), which, due to its reliance on a market-sampling program that did not differentiate between locally caught and imported seafood, systematically over-reported its catches. Officially reported catches potentially underestimate capture fisheries by a factor of two between 1950 and 2010 for all countries surrounding the Arabian Gulf except the UAE. Discards, mainly from shrimp trawlers, correspond to 18% of total landed catch. Based on the catch data, fisheries in the Arabian Gulf is likely to have reached their potential.

Projections of changes in distributions of marine species suggest that climate change is expected to have severe impacts on marine biodiversity and fisheries in the Arabian Gulf region. We found a high rate of local extinction (up to 35% of initial species richness) by 2090 relative to 2010 under the RCP 8.5 scenario. Species invasion is low (up to 5% of the initial species richness). As a result, many areas in the Gulf are projected to experience a net loss in biodiversity. Spatially, local extinction is highest in the southwestern part of the Arabian Gulf, off the coast of Saudi Arabia, Qatar and the UAE. In contrast, species invasion is only limited to small areas in the northern part of the Arabian Gulf, off the coast of Kuwait and northern Iran. Most parts of the Arabian Gulf, and in particular areas in the south and southwestern part of the Gulf, are projected to experience a decline in the sum of habitat suitability for all species.

For marine fishes and invertebrates, the projected pattern of changes in habitat suitability should provide useful indicators of climate change impacts on their diversity. However, the magnitude of changes in habitat suitability is more uncertain. Note that in the context of this report, habitat changes imply changes in the combination of temperature and salinity in the future compared to present conditions. In other words, changes in habitat suitability for a species refers to the experienced combination of changes in salinity and temperature at a given point in time by that species, relative to its niche for those parameters as defined by observed global occurrences. In this context therefore, habitat does not denote biogenic features such as 'reef' or 'seagrass' a given species may typically associate with for refuge and/or forage. For charismatic megafauna, confidence in the projected vulnerability to climate change is lower than those for fishes and invertebrates because it is more difficult to characterize the environmental preferences and tolerance of these species. Ecological characteristics beyond those considered in modelling efforts here (including importance of forage and vulnerability of individual life-history stages to environmental changes) are also likely to factor more strongly into an assessment of their vulnerability to climate change than for fishes and invertebrates. On the whole, incidental capture in fishing nets, coastal and offshore development, pollution, boat traffic, oil and gas exploration, and biotoxins associated with red tide events may cause greater harm, in the short and long term, to these species, and thus be more important to mitigate, than climate change.

Overall, results showed reduced future catch potential for several countries on the western side of the Arabian Gulf[3], with projections differing only slightly between models. Qatar and the UAE are particularly affected, with more than a 26% potential drop in future commercial fish catch potential.

Results from the vulnerability assessment integrating changes in catch potential with socio-economic indicators showed the fisheries of Iran and Oman as most vulnerable to the impacts of climate change. The UAE and Iraq were labelled as of "medium vulnerability", while Kuwait

[3] The countries on the western side of the Arabian Gulf are considered to be Iraq, Kuwait, Saudi Arabia, Bahrain, Qatar, UAE, and Oman.

and Saudi Arabia currently exhibited low vulnerability to climate change impacts on their fisheries. The fisheries of Bahrain and Oman are the most vulnerable to climate change. Our assessment provides a general indication of the potential vulnerability at the national level. The specific vulnerability of coastal communities to climate change impacts on fisheries would require more detailed, bottom-up community-specific studies. Also, specific limitation of the indicators and the methods used in the vulnerability assessment should be noted when interpreting the findings.

Given the potential climate change impacts on biodiversity throughout the Arabian Gulf, to be effective and maximise the resilience of future ocean ecosystems, conservation and management measures and the entities in charge of management will need to be adaptive. The adoption of monitoring programs designed for a changing ocean, and the subsequent inclusion of data to improve monitoring is thus important. There is also a need to increase the robustness and enhance the resilience of conservation measures, such as effective and enforced fisheries policies as well as Marine Protected Areas (MPA). Existing MPAs that are strategically located to see increases in biodiversity under future climate change scenarios need to be strengthened. Implementing networks of MPAs throughout the region and particularly in considered locations may also increase the likelihood of successfully conserving species following climate change-induced range shifts.

1. Introduction

Marine biodiversity, ecosystem health and fisheries are currently threatened by overfishing, but also by pollution and other anthropogenic impacts (Pitcher and Cheung 2013). Climate change further challenges our ability to devise sustainable management and conservation plans to maintain ecosystem services, as it has begun to alter ocean conditions, particularly water temperature and various aspects of ocean biogeochemistry (Gattuso *et al.* 2015). Marine biodiversity responds to shifting temperatures and other ocean conditions through changes in organismal physiology and phenology, as well as population dynamics and distributions (Pauly 2010; Poloczanska *et al.* 2013; Pörtner *et al.* 2014). These responses to ocean–atmospheric changes have been projected to lead to altered patterns of species richness (Cheung *et al.* 2009; Jones and Cheung 2015), changes in community structure (MacNeil *et al.* 2010), ecosystem functions (Petchey *et al.* 1999), and consequential changes in marine goods and services (Cheung *et al.* 2010; Sumaila *et al.* 2011; Madin *et al.* 2012).

Given the unique characteristics of the Arabian Gulf - particularly its extreme environmental conditions, the array of human disturbances it is exposed to, and the high sensitivity of its biota to environmental fluctuations as species are close to their environmental limits (Cheung *et al.* 2009; Buchanan *et al.* 2015) - climate change should have substantial implications for its marine ecosystems and fisheries. Extreme seasonal temperatures and salinity fluctuations select for species with high tolerance or adaptability to such short-term changes (e.g., as exhibited by some corals; see Kinsman 1964) creating a 'provincial barrier' for short-range endemics (Briggs 1974; Burt *et al.* 2011). Consequently, the Gulf is a region that is relatively species poor (Jones *et al.* 1978; Gray 2002; Coles 2003; Zolgharnein *et al.* 2010), at least in comparison with the open Indian Ocean (Coles 2003). However, as part of the Western Indian Ocean province of the Indo-West Pacific ecoregion (Spalding *et al.* 2007), which hosts a very distinct assemblage of species (e.g., 14.2% of fish in the Western Indian Ocean are endemics; Briggs and Bowen 2011), the Gulf is considered a biologically valuable region (see Olson and Dinerstein 1998). The Arabian Gulf's marine ecosystems are currently being affected by a variety of human activities, including hydrocarbon pollution, wastewater, desalination of sea water, coastal development, and overfishing (Sheppard *et al.* 2010; Sale *et al.* 2011; Burt 2014; Naser 2014; Elhakeem and Elshorbagy 2015). Additional declines have been caused by increases in sea surface temperature (SST) (e.g., Burt *et al.* 2013), with changes of +0.57°C recorded between 1950 and 2010 (Shirvani *et al.* 2014). Other climate change impacts that will affect the Arabian Gulf include ocean acidification, decline in oxygen content, sea level rise, increased UV exposure and, possibly, increases in extreme weather events. These changes are expected to impact marine organisms and the associated ecosystem goods and services we derive from them, such as fisheries.

Although many marine organisms in the Arabian Gulf have demonstrated high heat-tolerance relative to populations in other parts of the world (Sheppard 2003; Riegl *et al.* 2012; Hume *et al.* 2015; Hume *et al.* 2016), warming has already impacted some of the more vulnerable marine species in the region (Sheppard *et al.* 2010). For example, corals have been exposed to major disturbances (Bento *et al.* 2016), including water temperatures between 35 and 37°C at least five times since the late 1990s, causing extensive coral bleaching (Coles and Riegl 2013) associated with considerable loss of coral cover (Grizzle *et al.* 2016). In 1996 and 1998, summer SST was 1.5 to 2.5°C above normal, with temperatures exceeding 36°C for 3 weeks. Stands of *Acropora* sp. were almost eliminated over 40 reefs along the cost of the United Arab Emirates (UAE) by 1999 (George and John 2000; Riegl 2002; Sheppard and Loughland 2002). Overall, about 70% of the Gulf's reefs have essentially disappeared in a few decades (Sheppard 2016) and this has been associated with a significant decline in fish species richness. While substantial declines in stress-sensitive species are expected with increasing temperatures, results from a number of long-term studies investigating benthic community structure across the region suggest that coral communities may persist within an increasingly disturbed future environment, albeit in a much more structurally simple configuration (Burt *et al.* 2008; Riegl *et al.* 2012; Bento *et al.* 2016). So far, a comprehensive assessment of climate change impacts on the Arabian Gulf marine biodiversity and fisheries has not been undertaken.

This study aims to understand the vulnerability of Arabian Gulf marine biodiversity and fisheries to climate change. Firstly, we assessed the current status and trends for biodiversity and fisheries in the Arabian Gulf. We then applied simulation modelling approaches to assess the impacts to, and vulnerability of, marine biodiversity and fisheries to climate change. Finally, we discuss the implications of these impacts for conservation and fisheries management policies in the region.

2. Materials and methods

2.1. Study area

The Arabian Gulf is bordered by Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates (UAE), all signatory members of the Regional Organization for Protection of the Marine Environment (ROPME), created in 1978. It is a semi-enclosed marginal sea that is bounded in the north, for the most part, by the coast of Iran with the Shatt al-Arab river delta at the western end, and in the south, mainly by the

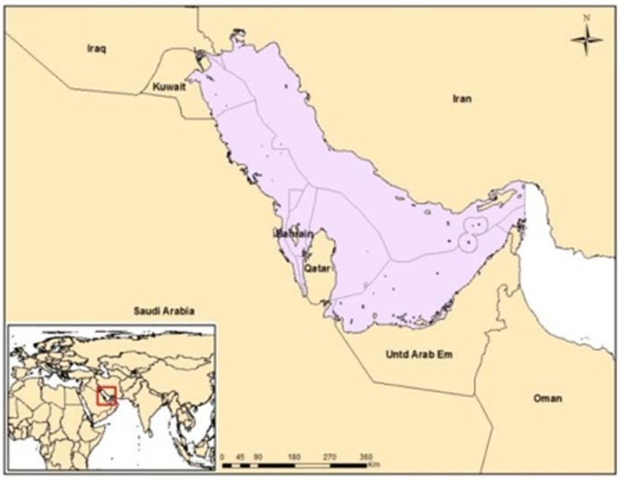


Figure 2-1: The Arabian Gulf as defined in this report (highlighted in purple), showing the approximate extent of actual and/or claimed Exclusive Economic Zones (EEZs) as used here, notably to allocate fisheries catches. Note that the maritime limits and boundaries shown on this map are not authoritative regarding the delimitation of international maritime boundaries

coasts of Saudi Arabia, the eastern end being the northwestern limit of the Gulf of Oman at the Strait of Hormuz (24º to 30º30'N; 48º to 56º25'E1; see Figure 2-1).

Ecologically, the Arabian Gulf is a relatively shallow semi-enclosed sea with a depth range of 10 to 93 m, averaging 36 m, a length of 990 km, a width ranging between 56 and 370 km, and a total surface area of 239,000 km² (Kämpf and Sadrinasab 2005). It has a gently sloping terraced shelf punctuated by numerous islands that formed as part of an extensive sabkha (i.e., salt flat see Al-Farraj 2005). The tidal range varies between 0.5 and 4.0 m. Maximum wave height was recorded at 5.5 m, and tides can flow at rates of up to 0.8 $m \cdot s^{-1}$ (Rakha *et al.* 2007). Water temperature ranges from 20ºC in winter to more than 30ºC in summer, with maximum salinities of 48 psu (Kinsman 1964), averaging 40 psu (Wright 1974), and exceeding 70 psu in lagoons (e.g., in Saudi Arabia) (Jones *et al.* 1978). Freshwater influx within the Gulf originates from 200 underground water springs, 25 springs from the Zagros Mountain, and 8 major rivers, notably the Euphrates and Tigris with water merging into the Shatt al Arab and flowing into the Gulf. These physical and environmental conditions make the Gulf a sedimentary environment (Riegl *et al.* 2010) that is conducive to the growth of mangroves, algae and seagrasses, providing habitat for a multitude of marine species and also protecting the coastline from degradation (Zahed *et al.* 2010).

Primary productivity is high at certain times of the year, with an increasing gradient in phytoplankton species richness and biomass from the Shatt Al Arab area (low species diversity, high biomass and production) to Kuwait, the Gulf of Oman, and the Strait of Hormuz (high species diversity, low biomass and production; see Subba Rao and Al-Yamani 1998).

2.2. Marine biodiversity in the Arabian Gulf

To perform assessments of the impact of climate change on the marine biodiversity in the Gulf, we extracted biodiversity, distribution, and biology data for the region from FishBase (www.fishbase.org) and SeaLifeBase (www.sealifebase.org) after enriching these databases with records from the Gulf. Specifically, we updated the coverage of all aspects of the species' biology making up its ecosystems, focusing on 56 "priority species", based on feedback with stakeholders. These included 48 of the most important species to fisheries in the Arabian Gulf (by weight), critical biogenic habitats for marine biodiversity (three species of seagrasses), and charismatic non-fish species that are also vulnerable or endangered (hawksbill and green marine turtles, dugongs, and two species of dolphins) (see Annex I and Annex II).

2.3. Fisheries catch reconstructions

We undertook fisheries catch reconstructions for each country in the Gulf region from 1950 to 2010 to improve upon the quality of catch data available through the United Nations Food and Agriculture Organization (FAO). These reconstructions are performed in six steps and provide estimates for all fisheries sectors and components (Zeller *et al.* 2007) by country. First, we identified and sourced existing reported catch time series (e.g., FAO and national data). Second, we identified sectors, time periods, species, gears, etc., that are not covered in FAO or national data. Third, we acquired all available alternative information sources addressing the data gap via extensive literature searches and consultations with local experts. Fourth, we developed data anchor points in time for missing data items. Fifth, these were projected to country-wide catch estimates and interpolated for the time periods between data anchor points. Lastly, we derived final total catch time series estimates, combining reported catches from FAO or national data, and the estimated catches that had been omitted in these official datasets.

We then improved upon the spatial resolution of these data by allocating the reconstructed catches to a global 0. 5^{o} latitude x 0. 5^{o} degree longitude cell grid system (i.e., about 180,000 maritime cells globally) using a rule-based approach. The rule-based approach allows the catch to be allocated directly to the half-degree cells based on the constraints provided by the distributions of various marine taxa. Also, the allocation is constrained by the accessibility of foreign fleets to the EEZs of various countries and this information is obtained from the SAU fishing access database (see www.seaaroundus.org for details of the method). In addition, for the reconstructed catch data, we first pre-assigned catches to the EEZ or EEZ-equivalent waters of a given fishing country and assigned the small-scale fisheries to the Inshore Fishing Area (IFA) which is the waters within 50 km from shore or waters up to 200m depth, whichever comes first. Only human inhabited landmasses have this IFA feature. So, this approach prevents domestic catches showing up in the EEZs of the wrong countries (Zeller et al. 2016). The Arabian Gulf region encompasses about 100 such cells. The allocation process combines catches by taxon, fishing nation and area fished (i.e., FAO statistical areas) with known ecological species distributions, broad habitat preferences, and fishing access information (Zeller *et al*. 2016). The result of this spatial allocation process is that catches are assigned to smaller spatial units (cell grid) that are more meaningful in ecosystem and ecological terms. We define EEZ claims or EEZ-equivalent claims based either on existing claims by a given country as known to us, or based on the basic principles underlying the United Nation Convention on the Law of the Sea (UNCLOS) articles related to EEZs. We do not claim the boundaries proposed by us to be politically or legally representative. For time periods pre-dating EEZ declarations, we assume free access to these waters, but treat them as EEZ-equivalent.

2.4. Projecting climate change impacts on marine biodiversity

The current and future distributions of the prioritized 56 marine species are here modelled using an environmental niche approach (*sensu* Hutchinson 1957). This method quantifies the environmental preferences of marine species and projects their potential distribution according to present and future environmental conditions.

2.4.1. Occurrence records and environmental data

To model species' environmental niches we collated global occurrence records and environmental data from a variety of sources. First, species presence/occurrence data were obtained from the Ocean Biogeographic System (OBIS, http://www.iobis.org, accessed in 2015) and the Global Biodiversity Information Facility (GBIF, http://www.gbif.org/). All points deemed erroneous were removed based on known environmental preferences and geographic limits, as defined in FishBase (Froese and Pauly, 2015) or obtained from OBIS-SEAMAP information (http://seamap.env.duke.edu/). Second, a set of environmental parameters known to influence marine species distribution were gathered at a global gridded scale. These included: sea surface temperature (SST) (1950-2013, World Ocean Atlas 2013); sea bottom temperature (1950-2013, World Ocean Atlas 2013); sea surface and bottom salinity (1950-2013, World Ocean Atlas 2013); sea surface and bottom nutrients concentration (1950-2013, World Ocean Atlas 2013); bathymetry; sea surface and bottom oxygen concentration (1950-2013, World Ocean Atlas 2013); Chlorophyll*a* concentration (2006-2015, MODIS-AQUA); particulate organic matter (2006-2015, MODIS-AQUA); and euphotic depth (2006-2015, MODIS-AQUA). The spatial data for each annual environmental climatology were re-gridded onto 0.25^o latitude x 0.25^o longitude resolution using a spline interpolation method (Legendre and Legendre 1998).

2.4.2. Modelling environmental niches

The environmental niche of each species was quantified using three separate models: the Non-Parametric Probabilistic Ecological Niche (NPPEN) model (Beaugrand *et al.* 2011); the the Bioclimate analysis and prediction (BIOCLIM) model (Busby 1991), and the Ecological Niche Factor Analysis (ENFA) model (Hirzel and Arlettaz 2003).

First, for each of the 56 focal species, the models quantified individual species' environmental envelope by estimating the best combination of environmental conditions, based on all of the parameters listed above, that describe its existing global occurrence. Sea surface and sea bottom environmental conditions were used for pelagic and demersal species respectively. Secondly, we used these species-specific environmental envelopes to project the probability of occurrence of a given species in each spatial cell of the oceans according to environmental conditions associated with that cell. Next, using projected future sea surface temperature and salinity, we projected current (2000-2020), mid-21st century (2041-2050) and end of 21st century (2080-2100) species distributions, based on high-resolution modelled hydrological conditions (temperature and salinity) of the Arabian Gulf from the Regional Oceanographic Modelling group of the AGEDI's Local, National, and Regional Climate Change (Edson *et al.* 2015). The oceanographic model projected changes under the Representative Concentration Pathway (RCP) 8.5, representing a high greenhouse gas emissions, business-as-usual scenario that results in a net radiative forcing of 8.5 Wm^{-2} (Moss *et al.* 2010). For the current period, we calculated the spatial anomalies of the high resolution (0.0275^o latitude x 0.0275^o

longitude) model outputs over a coarser resolution grid (0.25 ° latitude x 0.25° longitude). We then applied the spatial anomalies of both the current and future periods to the global environmental data described above to correct for the bias between modelled outputs and global data products from the synthesis of observational data. This procedure helped retain the high resolution spatial features of the model outputs. We then projected the spatial distribution of the 56 species using the three environmental niche models and the processed hydrological model outputs (i.e., based on climatological annual averages of predicted changes in salinity and temperature). The projected current and future spatial distributions of each species were further limited to the depth range of the species and their affinity to the coast.

Using results from projected changes in distributions, we estimated the impacts of climate change on the diversity of the 56 species using four indicators: rate of species invasion, rate of species local extinction, and sum of habitat suitability (i.e., index of habitat biodiversity suitability (HBS)). Rate of species invasion was calculated as the number of species newly occurring in a cell by 2050 (average between 2041 and 2050) and 2090 (average between 2080 and 2100) relative to the number of species in that cell in 2010 (average between 2000 and 2020). Rate of species local extinction represents the number of species disappearing from a cell relative to the number of species in that cell in 2010. Changes in HBS were estimated by subtracting the sum of the probability of occurrence for all species in 2050 and 2090 from that of 2010 for each cell.

> Note that from here on onwards when referring to habitat changes we imply changes in the combination of temperature and salinity in the future compared to present conditions. In other words, changes in habitat suitability for a species refers to the experienced combination of changes in salinity and temperature at a given point in time by that species, relative to its niche for those parameters as defined by observed global occurrences. In this context therefore, habitat does not denote biogenic features such as 'reef' or 'seagrass' a given species may typically associate with for refuge and/or forage (e.g., hawksbill marine turtle or dugong).

2.5. Vulnerability of charismatic species

In this report we focused on the following charismatic species: the dugong (*Dugong dugon*), Indo-Pacific humped-back dolphin (*Sousa chinensis*), Indo-Pacific bottlenose dolphin (*Tursiops aduncus*), green sea turtle (*Chelonia mydas*), and hawksbill sea turtle (*Eretmochelys imbricata*). Current and future habitat suitability of these species in the Arabian Gulf were projected using the modelling methods as described under section 2.4 above. The predicted changes in habitat suitability for charismatic species were used as indicators of sensitivity, and thus vulnerability, of these species to climate change impacts.

As indicated above, the predicted habitat suitability of charismatic species is defined by a limited subset of hydrological conditions that are available from the regional oceanographic model of the Arabian Gulf (Edson *et al.* 2015). **Thus, it may not include the full range of environmental and ecological factors affecting the distribution of sea turtles and marine mammals. Also, we did not predict habitat suitability for specific life stages (e.g., foraging or nesting populations), which may be more or less sensitive to environmental changes**. These methodological limitations should be taken into account when interpreting our projections, and the projected future distributions of charismatic species should be considered only as an indicator of their relative vulnerability to climate change.

2.6. Vulnerability of national economies to climate change impacts on fisheries

Climate change, primarily through the effects of rising global atmospheric temperature, is having an increasing impact on fisheries, including via coral bleaching, more frequent and severe storms, and ocean acidification. The Intergovernmental Panel on Climate Change (IPCC) defines 'vulnerability' as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change" (IPCC 2007).

Vulnerability assessments have been used in various disciplines to assess the susceptibility of natural or human systems to negative impacts as a result of human activities or natural pressures (Füssel and Klein 2006). A vulnerability assessment of fisheries to climate change involves understanding the impacts of climate change on the biophysical and social components of marine ecosystems. Several different frameworks have been proposed to examine how vulnerable societies are to climate change (e.g., Béné 2009; Adger and Vincent 2005). Here we chose to assess the relative vulnerability of each country's fisheries to climate change as a function of three dimensions: *exposure*, *sensitivity and adaptive capacity* (IPCC 2001; Turner *et al.* 2003; Kasperson and Archer 2005; Smit and Wandel 2006; IPCC 2007; Allison *et al.* 2009). Exposure is the nature and degree to which fisheries are exposed to climate change. Sensitivity usually refers to the intrinsic degree to which national economies are dependent on fisheries and therefore sensitive to any changes in the sector. Adaptive capacity is the ability of a social system in the current context to anticipate, respond and adjust to changes from climate stresses, and to minimise, cope with, and recover from the consequences of climate change (Adger and Vincent 2005). Adaptive capacity includes elements of social capital, human capital, and the appropriateness and effectiveness of governance structures (Barros *et al.* 2015). Using this framework, a number of recent studies have highlighted the vulnerability of national economies to potential changes in their fisheries from climate change (Allison *et al.* 2009; Bell *et al.* 2011; Ekstrom *et al.* 2015). Livelihoods and national economies will therefore need to manage immediate changes and trade-offs imposed by climate change. They will also need to evolve in a way that allows them to develop positive adaptation mechanisms and seize the opportunities that may arise from climate change impacts (Brugère 2015).

We combined projections from the above described ecological simulation models with indicators of the social-economic realm to examine the vulnerability of the Gulf's national economies to the potential impacts of climate change on its marine fisheries. It is important to note that **for Saudi Arabia, Oman, and Iran, countries with fisheries in other seas beyond the Arabian Gulf, relevant variables in the vulnerability assessment were pro-rated to the proportion of total catches derived from the Arabian Gulf**[4] (Table 2-1).

Table 2-1 – Proportion of total catches (2000s) that were derived from the Arabian Gulf for each country bordering the Gulf

Country	Average annual total catch (tonnes)	Arabian Gulf Catch (tonnes)	Proportion in Arabian Gulf
Bahrain	38,600	38,600	1.00
Iran	162,120	121,803	0.75
Iraq	12,869	12,869	1.00
Kuwait	38,692	38,692	1.00
Oman	90,089	3,688	0.04
Qatar	12,072	12,072	1.00
Saudi Arabia	39,502	19,873	0.50
United Arab Emirates	39,508	39,508	1.00

2.6.1. Indicators

For each of the three dimensions (exposure, sensitivity, and adaptive capacity), we selected a number of indicators, derived from separate sets of variables, to calculate the overall vulnerability index (Table 2-2). Most were based on the criteria and assumptions listed in Allison *et al.* (2009). A comprehensive description of each indicator and its calculation is provided in Annex VIII.

2.6.2. Calculation of the vulnerability index

The vulnerability of each country to impacts on its fisheries due to climate change was calculated by taking the average of the standardized indices for each dimension of vulnerability. We took the average because of the lack of clear understanding of the interaction among these constituent components. There are many ways of combining the components, for example they can be summed or multiplied or a particular indicator within a dimension may be given more weight based on local evidence (Turner *et al.* 2003). However, we made no *a priori* assumption about the importance of each dimension, or indicator within

[4] Pro-rating was done by applying the ratio of the country's total EEZ to the country's EEZ area within the Gulf.

each dimension, in the overall sum to calculate the vulnerability of each country to climate change - *V = f (E, S, AC)*. Thus, each of the indicators is viewed as having an equal contribution (i.e., balanced weight) to a country's overall vulnerability (Sullivan *et al.* 2002). Previous studies have shown that vulnerability is robust to change in the weightings of its components and to different methods of calculations (i.e., averaging or multiplying) (Allison *et al.* 2009, Cinner *et al.* 2012).

A country with a high vulnerability score is assumed to have (i) high exposure to climate change; (ii) high level of fisheries contributions to its national economy and food security; and (iii) low ability to respond and adapt to the risks posed by climate change.

Table 2-2 - Indicators and their composite variables for each dimension used to assess the vulnerability of national economies to climate change impacts on fisheries

Indicators	Definition	Composite index	Variable[1]	Sources
Exposure				
Change in maximum catch potential	Projected change in maximum catch potential of each marine species exploited by each country, in the Arabian Gulf, under RCP 8.5 in the 2090s relative to current status	Change in catch potential from current status under climate change	Percent change in maximum catch potential under climate change	Results from environmental niche model (ENM) and fisheries modelling
Sensitivity				
Employment	Importance of the marine fishery sector to local livelihoods	Number of fishers in the marine fisheries sector	Number of fishers	Teh and Sumaila (2013)
		Number of fishers relative to other sectors	Proportion of economically active population (%) in the fishery sector	Teh and Sumaila (2013); The World Bank Group
Nutritional dependence	Importance of fish as a source of nutrition and whether the nutrition provided by fisheries is sufficient to support the health of people in the country	Country's dependence on fish as a source of protein	Fish protein as proportion (%) of all animal protein consumed	FAOSTAT (2015)
		Child malnutrition	Proportion of children under five years old who are malnourished (underweight)	WHO (2015)
Economic dependence	Dependence of a country's economy on its fisheries sector	Country's dependence on its fishery sector for revenue	Landed values as proportion (%) of total GDP	*Sea Around Us*
		Fisheries export value	Value of fisheries exports as proportion (%) of total exports	FAO FishStatJ (2016) UN Trade Statistics (2015)
		Total fisheries landings	Catch (tonnes)	*Sea Around Us*
		Poverty rate	Number of people below national poverty lines (% of population)	The World Bank Group (2016)
Coastal protection	The importance of marine ecosystem services to minimise risks and threats from climate change	Country's current dependence on marine systems for coastal protection	Number of people living in areas of elevation < 5 m (% of population)	The World Bank Group (2016)
		Country's future dependence on marine systems for coastal protection	Land area of elevation <5 m (% of population)	The World Bank Group (2016)

Indicators	Definition	Composite index	Variable[1]	Sources
Adaptive capacity				
Health	Average number of years that a person can expect to live	Life expectancy	Life expectancy at birth (years)	WHO (2015)
Education	Education level	Adult literacy rates	Number of people over age 15 that can read and write, both sexes (% of population)	UNDP (2015) – Human Development Reports
		School enrolment ratios	Number of tertiary aged people enrolled in tertiary education, both sexes (% of population)	UNDP(2015) – Human Development Reports
Governance	Public institutions ability to conduct public affairs, manage public resources, effectively implement decisions, ensure the rule of law, improve accountability, and tackle corruption. These are generally seen as essential elements of a framework within which economies can prosper.	Political stability and absence of violence	Perceptions of the likelihood of political instability and/or politically-motivated violence (-2.5 – 2.5)	Kaufman *et al.* 2010; The World Bank Group (2016)
		Government effectiveness	Perceptions of the quality of public services, the quality of the civil service and its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies (-2.5 – 2.5)	
		Regulatory quality	Perceptions of the ability of the government to formulate and implement sound policies that permit private sector development (-2.5 – 2.5)	
		Rule of law	Perceptions of the extent to which agents have confidence in and abide by the rules of society, the quality of contract enforcement, property rights, the police, and the courts (-2.5 – 2.5)	
		Voice and accountability	Extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media (-2.5 – 2.5)	
		Control of corruption	Perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests. (-2.5 – 2.5)	
Fisheries management	Resources allocated by a government to sustainably manage its fisheries	Marine Protected Areas (MPA)	Proportion of territorial sea protected (%)	IUCN and UNEP-WCMC (2014)

Indicators	Definition	Composite index	Variable[1]	Sources
Size of the economy	Countries with a stronger economy may be able to divert more resources to respond and adapt to climate change	Gross Domestic Product (GDP)	Total GDP	The World Bank Group (2016)
Employment alternatives	Availability of fisheries in different sectors	Economic diversity	Proportion of population employed in different sectors (diversity/complexity index)	ILO (2016), UN Data (2014), LABORSTA (2016), MIT (2016)

[1] ***For Iran, Oman and Saudi Arabia based on dependence from Arabian Gulf only or pro-rated to proportion of catch derived from Arabian Gulf only***

3. Results

3.1. Marine biodiversity in the Arabian Gulf

FishBase and SeaLifeBase now have data for almost 1,400 marine species thought to occur in the Arabian Gulf. Details for these species are available online through FishBase (Arabian Gulf ecosystem fish list here) and SeaLifeBase (non-fish list here). Records include 817 fish species (0.5% recorded endemics), 39 marine chordates other than fish (46% seabirds, 23% marine mammals, 13% sea turtles, 8% sea snakes, 10% other chordates), 480 invertebrates (so far, 5% endemics, all of which are annelid worms; 47% annelids, 26% molluscs, 19% arthropods, 9% cnidarians, 2% echinoderms, cyanobacteria and acanthocephalians), and 35 marine plant species (34% brown algae, 31% green algae, 23% red algae and 11% vascular plants). Information and data to populate the databases were gleaned from 257 published sources, 53% of which were journal articles, 22% books, 16% book chapters and the rest from internet and database sources. Biological and ecological data were obtained from 178 published sources for fish and from 79 sources for other vertebrates and invertebrates.

Comparison with previous studies reviewing the marine biodiversity in the Arabian Gulf was not possible as the only review available to us is that of Amini Yekta *et al.* (2014), who estimated that there are 84 species of molluscs present in the Gulf. SeaLifeBase lists 108 molluscs from several sources. In a recently completed, but not yet available study, a team of 41 experts, including participants from the region (Bahrain, Iran, Iraq, Kuwait, Qatar, Saudi Arabia and the United Arab Emirates) as well as from Australia, Japan, and the United States assessed the extinction risk of 457 marine bony fishes in the Arabian Gulf using the IUCN Red List Categories and Criteria at the regional level. The total number of Gulf fish species as assessed by the current study differs as lists were established based on available information gleaned from the literature, and as such may include misidentifications, records that cannot be verified, species that no longer occur in the region, etc. These will need to be evaluated on a species-specific basis by local experts and requests for deletions/substitutions submitted to Fishbase and/or SeaLifeBase with supporting information so that species status can be revised and corrections made where necessary and relevant.

Coverage of the 1,400 species in terms of biological and ecological parameters is shown in Figure 3-1A. Of these, 60% are fishes, 35% are invertebrates, 3% are other marine vertebrates (marine mammals, seabirds, sea snakes, sea turtles), and 3% marine plants (algae and seagrasses). As expected, there is more coverage of biological parameters for fishes than for non-fishes (particularly invertebrates), because of the scarcity of published information available from online bibliographical systems. For both databases, predator and prey data, size, length-weight and growth data are well covered, while spawning, reproduction and maturity are poorly covered. Figure 3-1B shows the 335 Arabian Gulf species that are Red Listed by the International Union for the Conservation of Nature (IUCN); 50% are bony fishes, 22% sharks and rays, 12% anthozoans, 5% seabirds, 4% cephalopod molluscs and the rest are marine mammals, sea snakes, sea turtles, crustaceans and bivalve molluscs. Thirty-one percent of listed species are categorised as Critical, Near Threatened, Vulnerable or Endangered. Figure 3-1C gives an overview of the 995 species with depth information in FishBase and SeaLifeBase; 65% are fishes, 24% invertebrates (mostly crustaceans, molluscs, echinoderms and corals), 7% sharks and rays, and 3% other marine vertebrates. The bulk of these species (95%) occur at a geometric mean depth of 100 m.

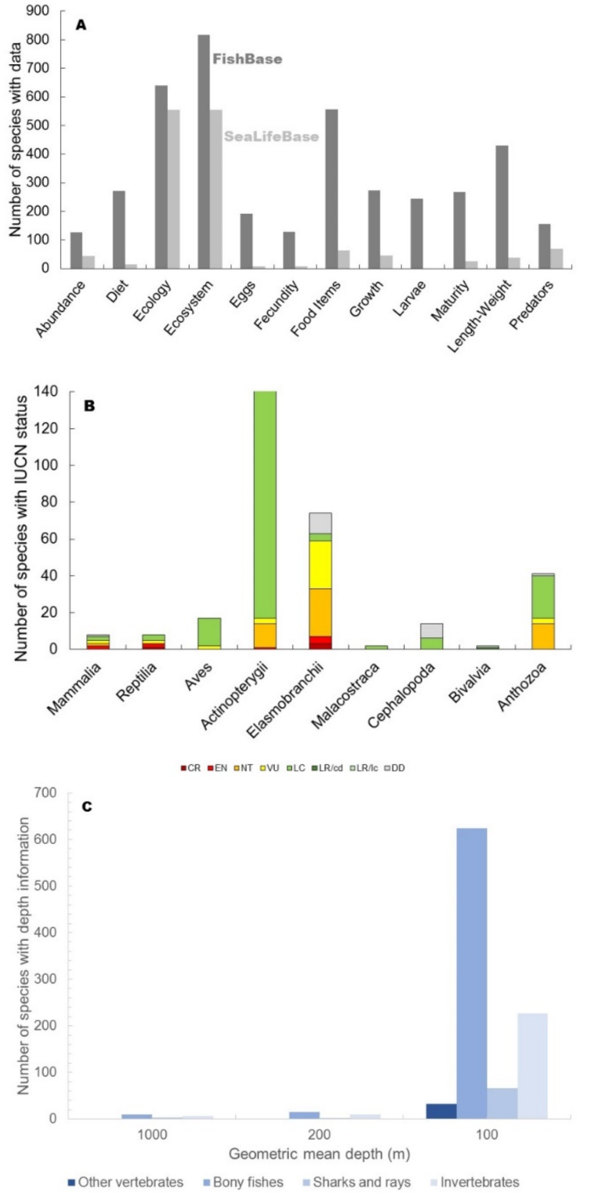


Figure 3-1: Coverage of the Arabian Gulf ecosystem in FishBase and SeaLifeBase: (A) Number of species (around 1,400) and type of data encoded in FishBase and SeaLifeBase, so far by species groups, (B) Number of species with IUCN status (335 red-listed species) in FishBase and SeaLifeBase, by species groups, (C) Number of species (995) with depth information by species groups. Ninety-five percent of species are found at depths of around 100 m.

3.1.1. Biogenic habitats

What we believe is the latest collated and standardised data available for coral reefs, seagrasses and mangroves of the Arabian Gulf are displayed in Figure 3-2. Extensive areas of seagrass are recorded along the coast of the UAE and Kuwait, with two important sites in Iran and one in Qatar. Note that coral reefs have suffered significant losses since the data used to develop the database from which Figure 3-2 was generated (Buchanan *et al.* 2015; Grizzle *et al.* 2016).

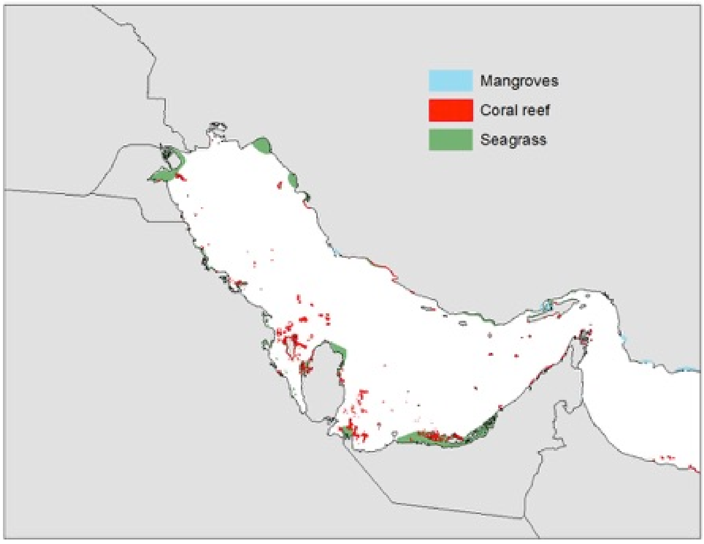


Figure 3-2: Mapping of mangroves (Spalding *et al.* 1997, 2010), coral reefs (UNEP-WCMC 2010) and seagrass (UNEP-WCMC 2005) in the Arabian Gulf

3.1.2. Fishes and invertebrates

Meta-data for the 56 priority species, including habitat information, size, depth range and trophic level information are presented in Annex II. The occurrence records (global) are presented in Figure 3-3. Occurrences of all of the species modelled have been recorded outside the Arabian Gulf; the Arabian Gulf only represents a subset of the habitat that these species inhabit. Therefore, in modelling their distribution, we used the global occurrence

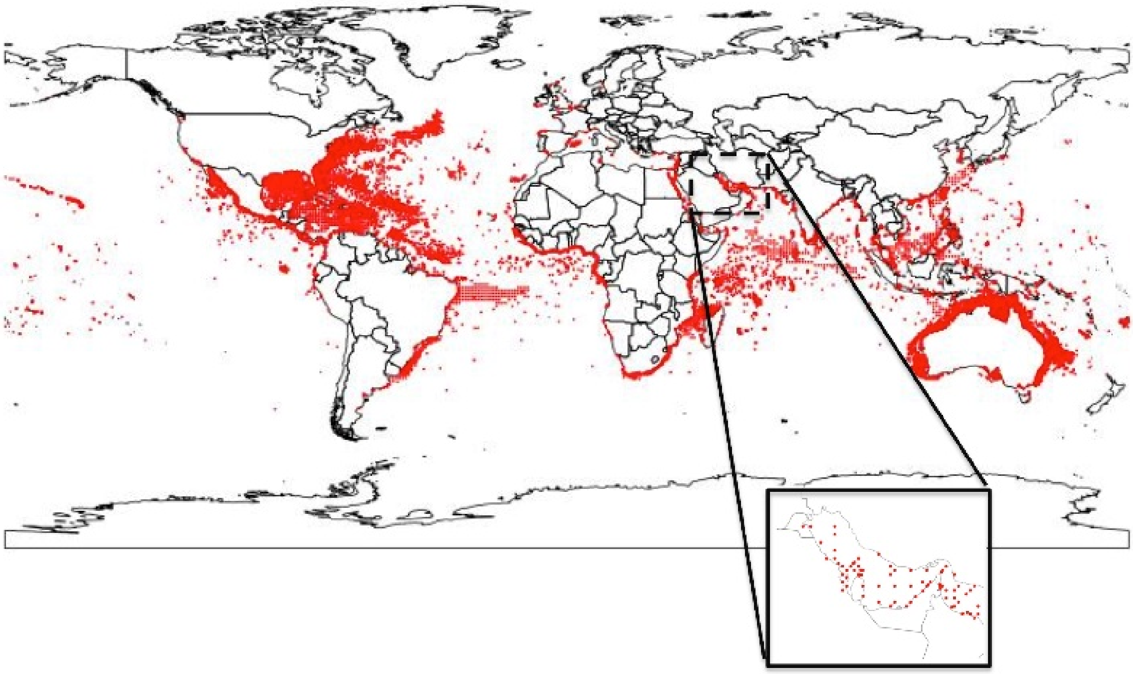


Figure 3-3: Map of occurrence records of the 57 species that were modelled in the world's oceans including the Arabian Gulf

records to capture the full range of environmental preferences and tolerances of each species.

3.2. Fishery catch reconstructions

For each country in the Arabian Gulf, time series of 'reconstructed catch' were generated. In other words, all the industrial, artisanal (small-scale commercial fishers whose catch is sold), recreational and subsistence catches (for direct consumption, not sale) in the Gulf were assessed and compared to the generally lower, officially reported catch. **For countries with access to waters other than the Gulf, catches derived from the Gulf *only* were included in analyses**. We also estimated the volume of discards from industrial fisheries (fish caught, but discarded at sea). A summary of the catch reconstruction work, by country, is presented below. For details on the methodology, including a definition of small-scale fishery by country, and findings refer to Al-Abdulrazzak and Pauly (2013).

3.2.1. Bahrain

Bahrain is the smallest of the Gulf States and the only island country in the region (Figure 2-1). Bahrain has a rich maritime history that includes fishing and pearling. The fisheries consist of an important artisanal sector, whose catches increased in the 2000s, in contrast to industrial catches that appear to plummet (Figure 3-4A). The reconstructed catch of Bahrain, based on Al-Abdulrazzak (2013), increased from 6,200 t in 1950 to 48,000 t in 1996, then declined and increased again to similar levels in the late 2000s. Reconstructed total catch corresponds to about 3.5 times landings reported by FAO on behalf of Bahrain. Rabbitfish (Family Siganidae), swimming crab (Portunidae), herring, shad, sardine and menhaden (Clupeidae), and fourlined terapon (*Pelates quadrilineatus*) were the major taxa in the catch, which also included a multitude of other species (Figure 3-4B). There are growing concerns over Bahrain's fisheries, including their continued use of illegal driftnets. Although catches appear to be increasing, it is likely that the decline of

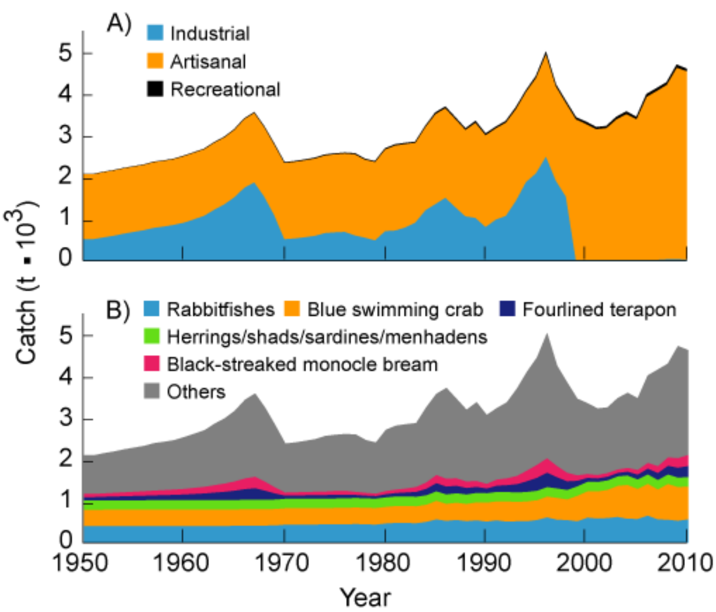


Figure 3-4: Reconstructed domestic and foreign catches taken in the EEZ of Bahrain. (A) by sector; (B) by taxon

traditionally targeted taxa is masked by previously discarded species being retained for consumption by the increasing immigrant community in Bahrain.

3.2.2. Iraq

Iraq has the smallest EEZ of the Gulf countries, at the mouth of the Shatt al-Arab River, formed by the confluence of the Euphrates and Tigris rivers about 200 km upstream (Figure 2-1). Consequently, Iraq's marine fisheries are less important than its freshwater fisheries, not considered here (see Jawad 2006).

Catches were predominately domestic and artisanal in nature, although the subsistence sector does exist and was reconstructed by Al-Abdulrazzak and Pauly (2013a), based on admittedly fragmentary evidence (Figure 3-5A). Domestic catches were in the order of 1,000-3,000 t·year^{-1} from 1950 to the early 1970s, then fluctuated between 10,000 and 30,000 t·year^{-1}, as peace and war alternated in the Shatt-al-Arab region. Overall, the reconstructed catches are 1.6 times those reported by FAO on behalf of Iraq, and are dominated by previously unreported catches of hilsa shad (*Tenualosa ilisha*), an anadromous fish. The rest of the catch is likely to resemble that of neighbouring Kuwait, whose taxonomic composition was used to disaggregate the non-hilsa marine catch of Iraq (Figure 3-5B), and thus assumed to consist of groups such as mullets (Family Mugilidae), croakers (Family Sciaenidae) and groupers (*Epinephelus* spp.).

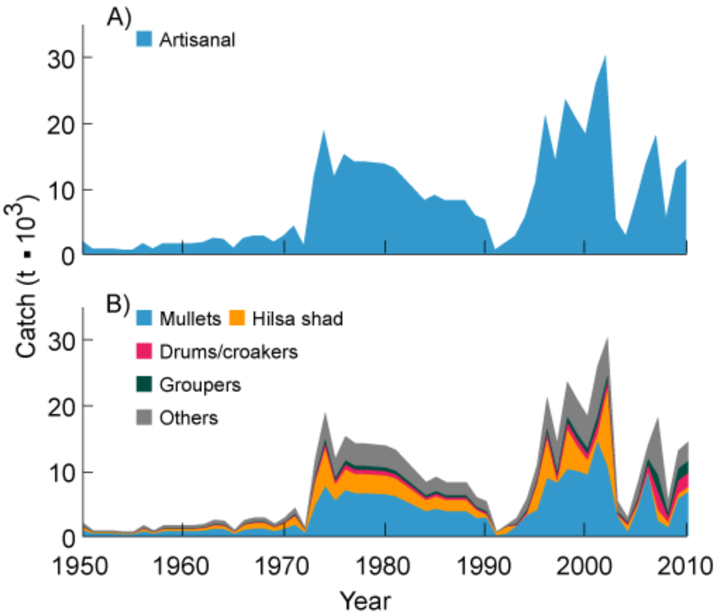


Figure 3-5: Reconstructed domestic and foreign catches taken in the EEZ of Iraq. (A) by sector; (B) by taxon

3.2.3. Iran (Gulf only)

Iran is the country with the longest coastline in the Arabian Gulf (Figure 2-1). This catch reconstruction, adapted from Roshan Moniri *et al.* (2013), concerns only Iran's fisheries in the Gulf and covers domestic industrial, artisanal (incl. weirs; Al-Abdulrazzak and Pauly 2013b), subsistence, recreational, and discards) (Figure 3-6A). Although the majority of catches within the EEZ are domestic, foreign catches by China, South Korea and some of Iran's neighbours were also documented starting in the 1980s (Figure 3-6B). The reconstructed domestic catch averaged 157,000 t·year^{-1} in the 1950s, slowly increased to 192,000 t before declining during the Iran-Iraq war (1980-1988), rapidly recovered and peaked at 400,000 t in 1997. It declined to around 170,000 t·year^{-1} in the late 2000s. These values correspond to a reconstructed catch 2.7 times the data reported by FAO (and adjusted for Iranian catches from outside of the Gulf), largely due to substantial under-reporting of artisanal catches. Catches were dominated by ponyfish (*Leiognathus* spp.), green tiger prawn (*Penaeus semisulcatus*) and blue swimming crab (*Portunus segnis*), but also included a tremendous variety of other fish species (Figure 3-6C). Overall, Iran's nominal management of fisheries is hampered by lack of key data, and the suppression of domestic and foreign illegal fishing.

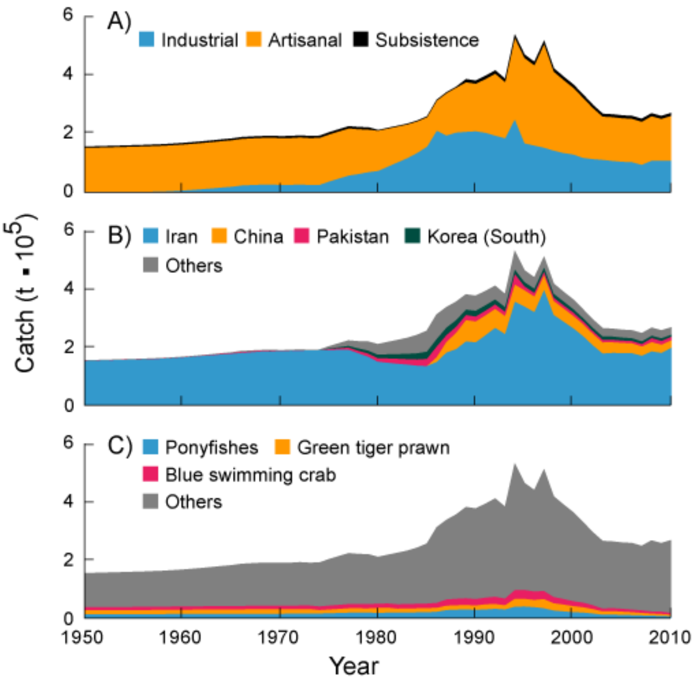


Figure 3-6: Reconstructed domestic and foreign catches taken in the EEZ of Iran (Gulf). A) by sector; B) by fishing country; C) by taxon

3.2.4. Kuwait

Kuwait is located in the northwest of the Arabian Gulf (Figure 2-1). Substantial artisanal and industrial fishing occurs in Kuwait's EEZ, in addition to a large subsistence and recreational component (although not visible in Figure 3-7A). Kuwait's catches have grown substantially over the past 60 years (Al-Sabbagh and Dashti 2009), and were reconstructed by Al-Abdulrazzak (2013a). The result is a total domestic catch estimate of about 8,700 $t \cdot year^{-1}$ for the early 1950s, increasing to a first peak of over 40,000 $t \cdot year^{-1}$ in the early 1970s, followed by decline in the late 1970s, due to the Iran-Iraq war. The second peak, at over 60,000 t, occurred in 1988, and was followed by a slow decline in total catches stabilizing at under 40,000 $t \cdot year^{-1}$ through the 2000s. Overall, this corresponded to a catch 6.4 times that reported by FAO on behalf of Kuwait, mainly due to discards from the trawl fishery being 10 times greater than finfish landings. Foreign fishing, notably by Iraq, only becomes visible in the 2000s (Figure 3-7B). Figure 3-7C shows a few of the major taxa caught in Kuwait: giant catfish (*Netuma thalassina*) whose catch is entirely discarded; sharks and rays (Elasmobranchii); natantian decapods (shrimps); and guitarfish (Rhinobatidae), also discarded. One of the first key management actions for Kuwait would be to find a way to utilize the vast by-catch of Kuwait's trawl fisheries that is currently discarded.

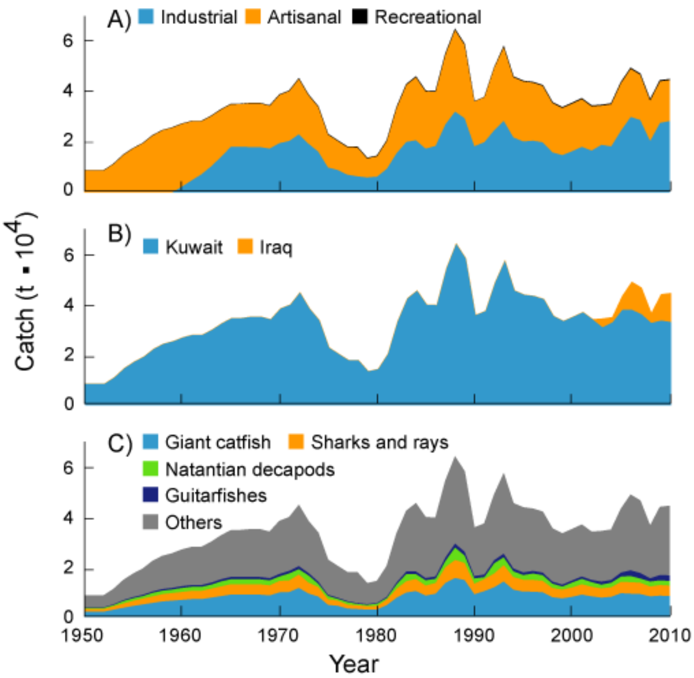


Figure 3-7: Reconstructed domestic and foreign catches taken in the EEZ of Kuwait. (A) by sector; (B) by fishing country; and (C) by taxon

3.2.5. Qatar

Qatar is a small country located on a peninsula abutting Saudi Arabia (Figure 2-1). Qatar's catches have increased sharply over the past decade due to increased fishing effort, driven by the growing demand from a rapidly expanding population. Catch reconstruction by Al-Abdulrazzak (2013b) suggests that domestic landings in the 1950s were about 1,000 t·year^{-1}, increased to nearly 20,000 t·year^{-1} in the 2000s, and were 38% higher than reported by the FAO on behalf of Qatar. While catches in the earlier years were dominated by industrial vessels (Figure 3-8A), mainly of foreign origin prior to EEZ declaration in 1974 (Figure 3-8B), more recently, domestic artisanal fleets predominate (Figure 3-8A). One of several reasons for the discrepancy between domestic reported and reconstructed catches is the omission of discards from Qatar's bottom trawl fishery. Between 1970 and 1993, the 3 bottom trawlers operated by the Qatari National Fishing Company (QNFC) discarded the equivalent of 30% of reported catches. The main taxa caught by Qatar are emperors (Family Lethrinidae), groupers (Serranidae), jacks (Carangidae), rabbitfish (Siganidae) and grunts (Haemulidae; Figure 3-8C). The reconstruction also highlighted the extent of illegal domestic fishing. For example, 14 tidal weirs ('*hadrah*'), a practice that has been banned since 1994, were detected by Al-Abdulrazzak and Pauly (2013b) along the Qatari coast on current Google Earth images.

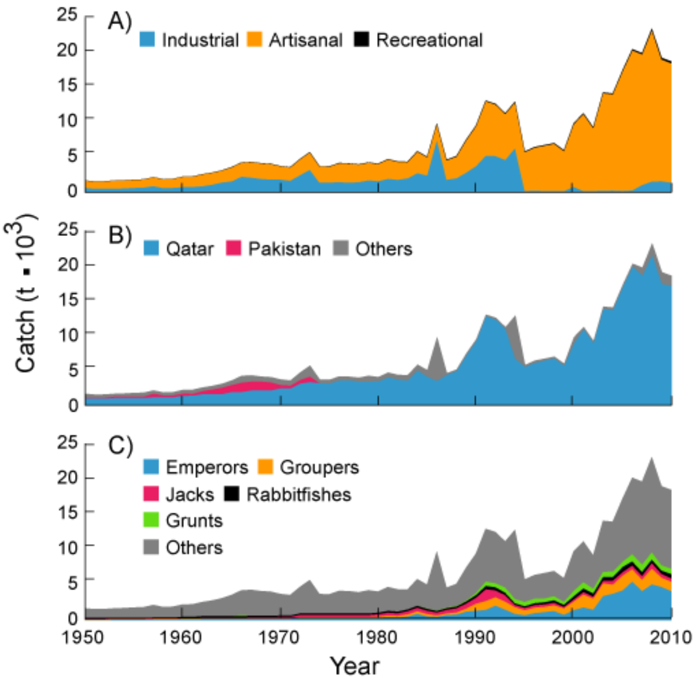


Figure 3-8: Reconstructed domestic and foreign catches taken in the EEZ of Qatar. (A) by sector; (B) by fishing country; and (C) by taxon

3.2.6. Saudi Arabia

Saudi Arabia has a longer coastline in the Red Sea than in the Gulf (Figure 2-1) but its Gulf fish catch is still considerable, but its fish catch in the Gulf appears higher. The bulk of Saudi fisheries in the Gulf are artisanal (Figure 3-9A); their motorization started in the early 1960s and was completed in the late 1980s. Domestic catches by Saudi Arabia in the Gulf were reconstructed by Tesfamichael and Pauly (2013) primarily based on data from the Regional Commission for Fisheries (RECOFI). Landings were found to increase from about 2,000 $t\cdot year^{-1}$ in the early 1950s to 50,000 $t\cdot year^{-1}$ in the late 2000s, with an intermediate phase, from the early 1960s to the early 1990s. High trawl catches and especially discards, contributed substantially to overall catches from 1950 to 2010. While the reconstructed Saudi catch as a whole (i.e., including catches in the Red Sea) is 2.1 times higher than FAO reports on behalf of Saudi Arabia, estimates are 2.4 times higher for catches in the Gulf only. The domestic fishery landed the majority of the catch (Figure 3-9B). Due to the nature of artisanal fisheries and Saudi's Gulf waters, which are generally shallow with sandy and muddy bottoms covered by seagrass beds, the catch (Figure 3-9C) consists mainly of a multitude of demersal fish and shrimp, both impacted by oil pollution, notably in 1991 (Mathews *et al.* 1993).

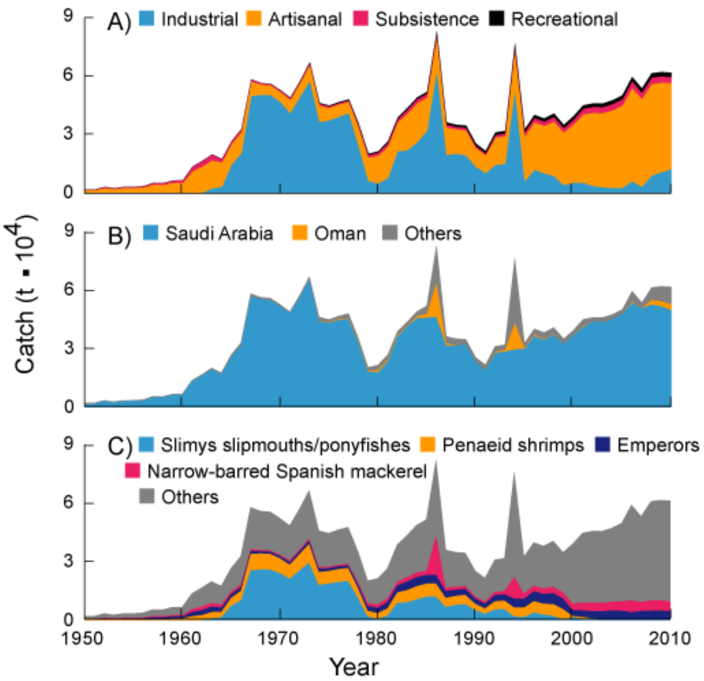


Figure 3-9: Reconstructed domestic and foreign catches taken in the EEZ of Saudi Arabia. (A) by sector; (B) by fishing country; and (C) by taxon

3.2.7. United Arab Emirates

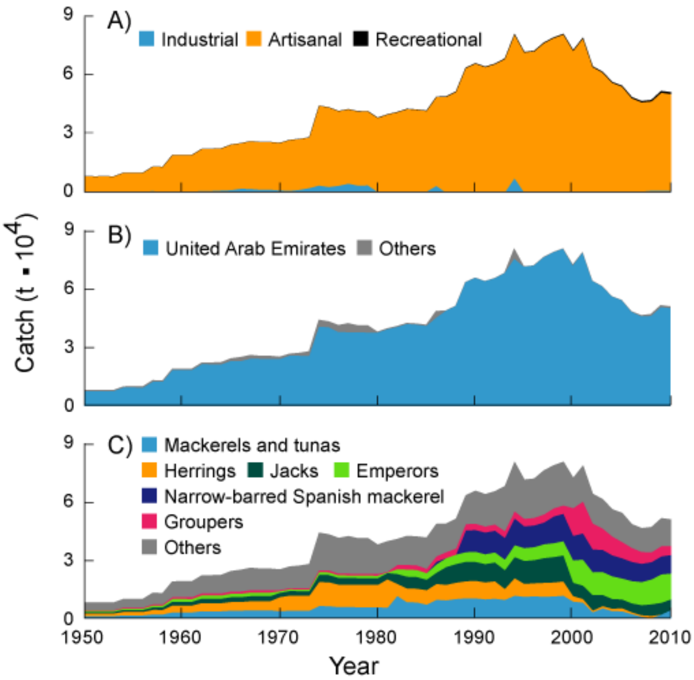


Figure 3-10: Reconstructed domestic and foreign catches taken in the EEZ of United Arab Emirates. A) by sector; (B) by fishing country; and (C) by taxon

The United Arab Emirates (UAE) has coasts on the Arabian Gulf (Figure 2-1) and in the Gulf of Oman. Catch reconstructions presented here, and based on Al-Abdulrazzak (2013c), only address landings for the UAE's Gulf coast. Domestic fisheries are small-scale in nature (Figure 3-10A), with little foreign or industrial fishing (Figure 3-10B), and occur mostly in Abu Dhabi, which comprises over 60% of the UAE's Gulf EEZ. Due to its reliance on a market-sampling program that did not differentiate between locally caught and imported seafood, the UAE systematically over-reported its catches (Morgan 2004). Al-Abdulrazzak (2013d), who considered this, estimated the UAE's catch, adjusted for Gulf EEZ waters only, as 8,000·t·year^{-1} in the early 1950s, increasing until reaching a peak at 80,000 t in 1999, then declining to 50,000 t·year^{-1} in the late 2000s. Overall, the figures reported by FAO on behalf of the entire UAE *over*-estimated reconstructed catches by 47%, despite the latter also accounting for subsistence and recreational catches, missed entirely by the market-sampling program. The major taxa caught in the UAE (Figure 3-10C) are mackerel and tuna (Family Scombridae), herring (Clupeidae), jacks (Carangidae), emperors (Lethrinidae), narrow-barred Spanish mackerel (*Scomberomorus commerson*) and groupers (Serranidae). Improving the UAE's catch reporting system appears essential if its fisheries are to be managed for sustainability.

3.2.8. All countries

Overall, catches from the Arabian Gulf increased from 1950 to 2000 from 200,000 tonnes to around 600,000 tonnes, then declining to about 400,000 tonnes in the 2000s (Figure 3-11 A-C). Gulf countries have primarily reported their artisanal and industrial catches and have substantially misreported their discards, as well as recreational, subsistence, and illegal fishing sectors. Our results suggest that all countries in the Gulf under-report their catches, with the exception of the UAE, which over-report theirs. We show that regionally, officially reported catches potentially underestimate capture fisheries by a factor of two between 1950 and 2010, and that discards, mainly from shrimp trawlers, correspond to 18% of total landed catch.

3.3. Vulnerability of marine biodiversity and fisheries to climate change

We predicted the current and future distributions of the 56 focal species for the period 2000-2020 and 2080-2099 (see Annex III for species-specific maps). Projections of changes in distributions of marine species suggest that temperature – driven climate change is expected to have severe impacts on marine biodiversity and fisheries in the Arabian Gulf. *Noting that projections are possible changes in habitat suitability as estimated by the methods used herein rather than actual predicted changes in abundance,* **the models projected high rate of local extinction (up to 12% of initial species richness) in the Arabian Gulf by 2090 (average between 2080 – 2099) relative to 2010 (average between 2000-2020) under the RCP 8.5 scenario (Figure 3-12A).** For projected changes in species richness, invasion and local extinction by 2050 relative to 2000, see Annex III).

Species invasion is low (up to 5% of the initial species richness). **Spatially, local extinction is highest in the southwestern part of the Arabian Gulf, off the coast of Saudi Arabia, Qatar and the UAE. In contrast, species invasion is only limited to small areas in the northern part of the Arabian Gulf, off the coast of Kuwait and northern Iran.** This projected pattern appears to be robust as indicated by congruence of all three models' results. Nonetheless, variability in the projections between models is visible for portions of the central

Figure 3-11: Total reconstructed catches from the Arabian Gulf region from 1950 to 2010.

Arabian Gulf. A drastic reduction in the total habitat biodiversity suitability for all species is shown in Figure 3-12B, underlying the climate driven perturbation of marine habitats in the region. This climate-driven perturbation in local and regional environmental conditions will make most of the southern Gulf unsuitable for species making up current biodiversity. In the future, only species with extreme adaptability particularly with regards to temperature, are likely to occur in this area. Projected habitat biodiversity suitability (HBS) increases in the northern part of the Gulf, potentially providing the only refuge for fauna in the Gulf.

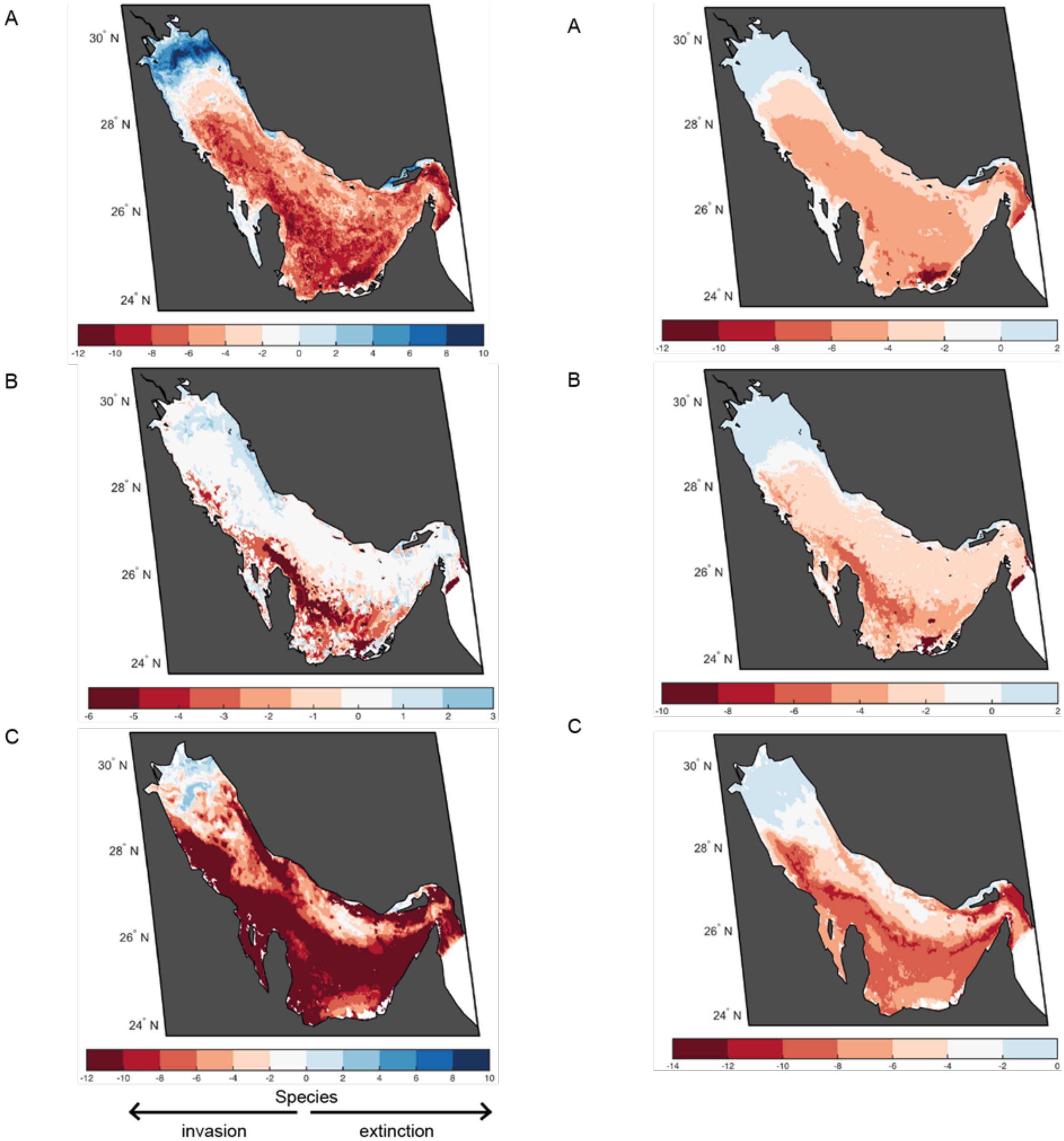
The climate-driven perturbation in local and regional environmental conditions will make most of the southern Gulf unsuitable for species making up current biodiversity. In the future, only species with extreme adaptability particularly with regards to temperature, are likely to occur in this area.

A graph showing the percent change in habitat suitability for all non-fish species in the Economic Exclusive Zones (EEZs) of the Arabian Gulf in 2050 and 2090 under the RCP8.5 scenario, as an average across all three models in presented in Annex VII.

Figure 3-12: Projected changes by 2090 relative to 2010 from (A) NPPEN and (B) ENFA and (C) BIOCLIM.

Rate of local extinction and species Invasion

Index of habitat biodiversity suitability (sum of predicted habitat suitability)



For Figure 3-12 (left panel), species invasion is represented by positive values while species local extinction is represented by negative values.

For Figure 3-12 (right panel), increasing habitat biodiversity suitability is represented by values to the right of the scale while decreasing habitat biodiversity suitability is represented by values to the left of the scale

3.4. Vulnerability of charismatic species

While models showed varying ranges of loss in habitat suitability for dugong, sea turtles and Indo-Pacific Humpback Dolphin in the Gulf, on the whole, future projections were largely inconclusive.

3.4.1. Dugong

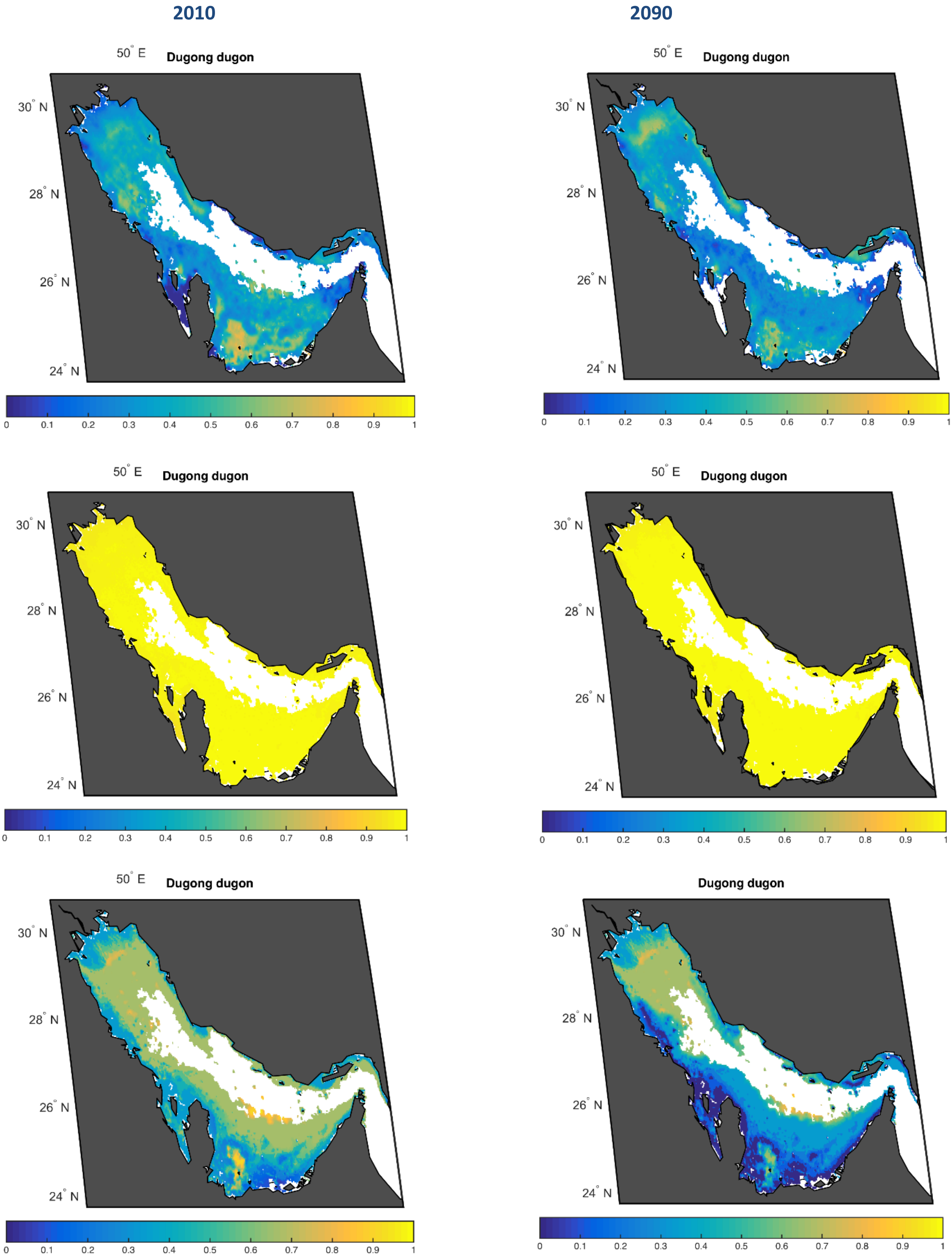
The Gulf is currently the major remaining habitat for dugong, after Northern Australia. Projections from BIOCLIM and NPPEN showed that the Gulf would become less hospitable to dugong, particularly around the southwestern region such as the waters around Bahrain (Figure 3-13). However, habitat suitability predicted by the ENFA model, the least conservative among the three models, showed essentially no loss of habitat suitability for dugongs under climate change. A graph showing an average across all three models of percent change in habitat suitability for dugong in the EEZs of the Arabian Gulf in 2050 and 2090 under the RCP8.5 scenario is included in Annex IV.

Note that all results show future modelled habitat suitability in the region according to projected changes in temperature and salinity relative to the preferred environmental niche of the marine mammal itself. Consequently, these projections do not take into account the fact that dugongs rely on seagrass for almost their entire diet, and the likely resultant changes in dugong's habitat suitability based on projected changes to seagrass distribution.

3.4.2. Hawksbill and green turtles

Projections from BIOCLIM and NPPEN, based on estimates of future temperature and salinity relative to the animal's environmental niche, showed a loss of habitat suitability for green and hawksbill turtles around the southwestern parts of the Gulf and near the Strait of Hormuz, with the latter model also showing loss of habitat in the northern parts of the Gulf (Figure 3-14 and Figure 3-15). Findings from the ENFA projections agree with these results, but the loss of suitable habitat in the south and southwestern Gulf were more severe. The projected patterns of changes in habitat suitability are similar between green and hawksbill turtles, except that NPPEN projects a more substantial habitat loss for green turtles along the Gulf coast. A graph showing an average across all three models of percent change in habitat suitability for green turtles in the EEZs of the Arabian Gulf in 2050 and 2090 under the RCP8.5 scenario is included in Annex V.

Figure 3-13: Projected 2010 (average of 2000-2020) and 2090 (average of 2080-2099) distributions and habitat suitability of dugong in the Arabian Gulf under RCP 8.5 using (upper) NPPEN, (middle) ENFA and (lower) BIOCLIM. Habitat suitability for given species scaled from 0 to 1, with 0 being not suitable and 1 most suitable.



White areas indicate a probability of occurrence for the species equal to zero, therefore it is equivalent to loss of habitat

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Figure 3-14: Projected 2010 (average of 2000-2020) and 2090 (average of 2080-2100) distributions of, and habitat suitability for, green turtles in the Arabian Gulf under RCP 8.5 using NPPEN (upper), ENFA (middle) and BIOCLIM (lower). Habitat suitability for given species is scaled from 0 to 1, with 0 being not suitable and 1 most suitable.

2000 **2090**

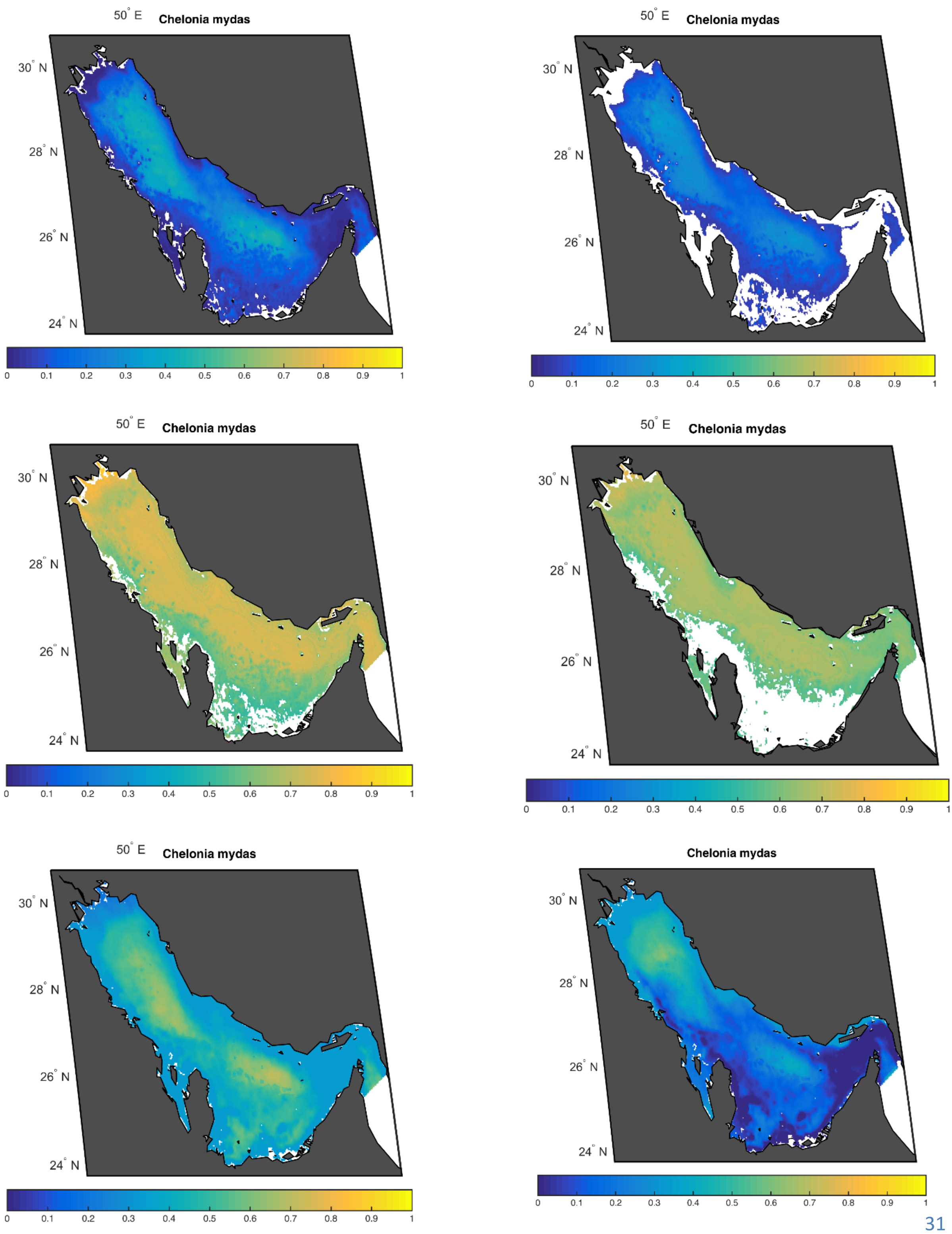
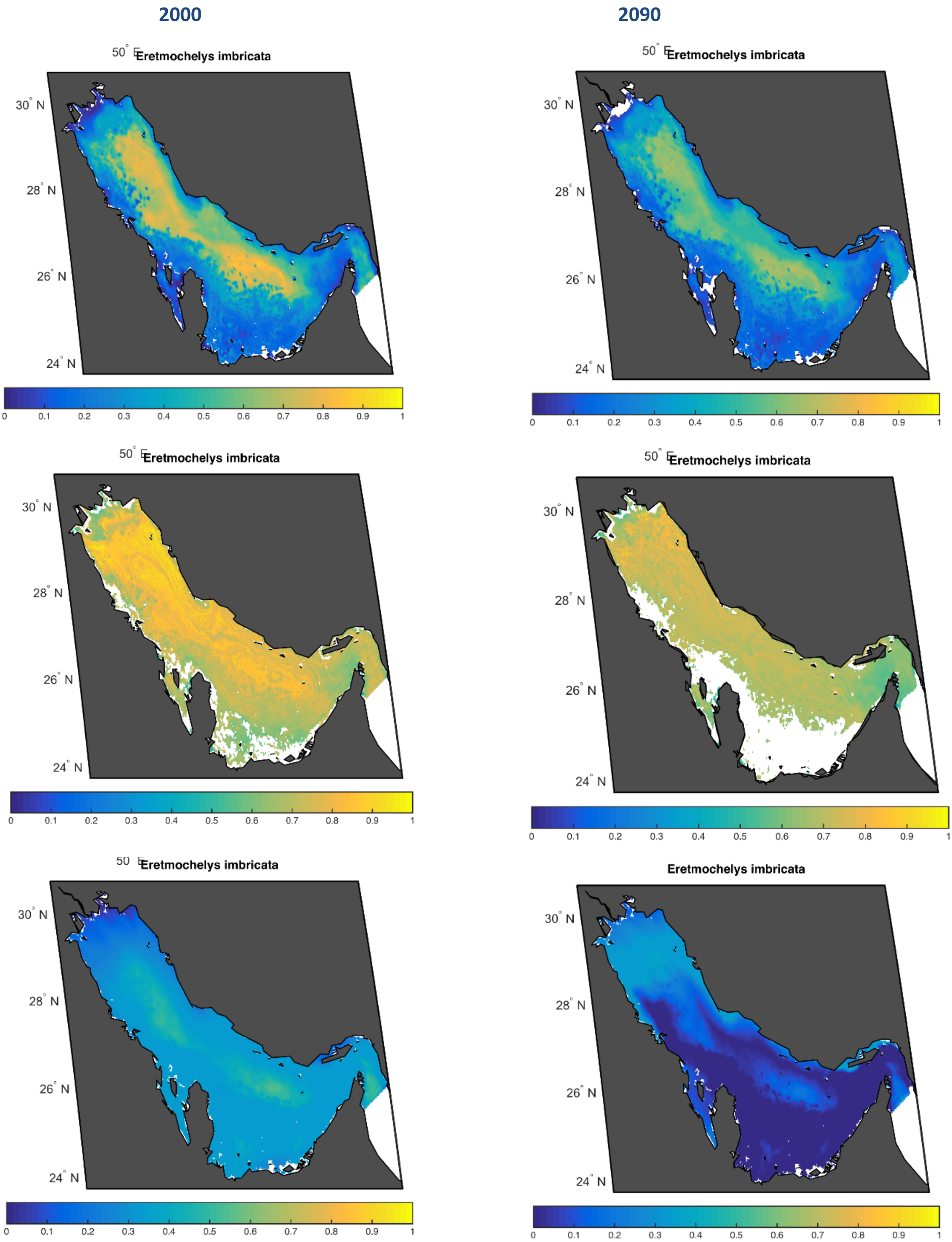


Figure 3-15: Projected 2010 (average of 2000-2020) and 2090 (average of 2080-2100) distributions of and habitat suitability for hawksbill turtles in the Arabian Gulf under RCP 8.5 using NPPEN (upper), ENFA (middle) and BIOCLIM (lower). Habitat suitability for given species is scaled from 0 to 1, with 0 being not suitable and 1 most suitable.

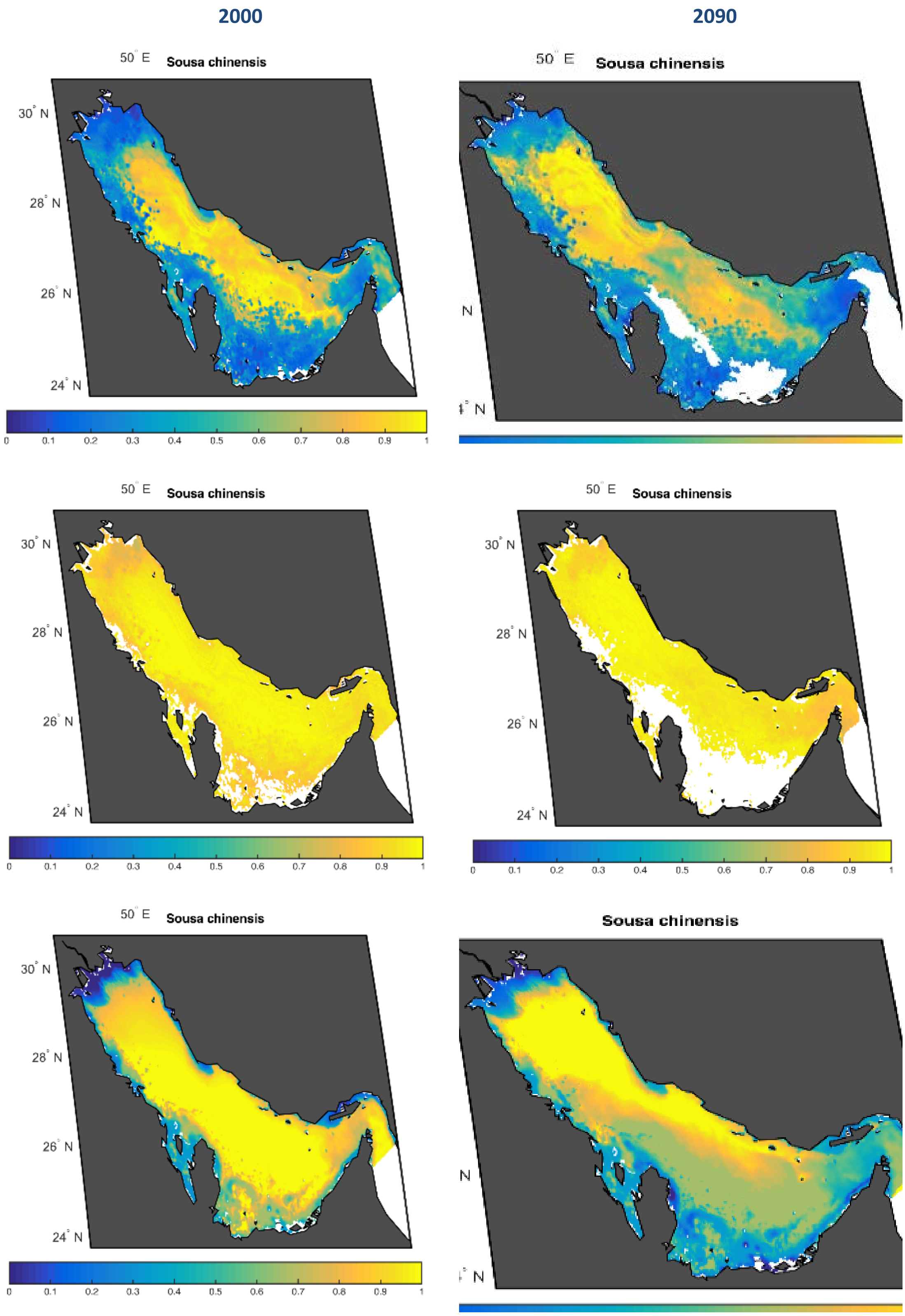


White areas indicate a probability of occurrence for the species equal to zero, therefore it is equivalent to loss of habitat

3.4.1. Indo Pacific dolphin

The BIOCLIM model projections showed loss of habitat suitability for Indo Pacific dolphins particularly around the southwestern parts of the Gulf. Projections based on NPPEN were similar, expanding to Bahrain and Qatar (Figure 3-16). ENFA model runs demonstrated uniform loss of habitat suitability throughout the lower three quarters of the Arabian Gulf. A graph showing an average across all three models of percent change in habitat suitability for Indo-Pacific Humpback Dolphin in the EEZs of the Arabian Gulf in 2050, 2090 under the RCP8.5 scenario is included in Annex VI.

Figure 3-16: Projected 2010 (average of 2000-2020) and 2090 (average of 2080-2100) distributions of and habitat suitability for Indo-Pacific Humpback Dolphin in the Arabian Gulf under RCP 8.5 using NPPEN (upper), ENFA (middle) and BIOCLIM (lower). Habitat suitability for given species is scaled from 0 to 1, with 0 being not suitable and 1 most suitable.

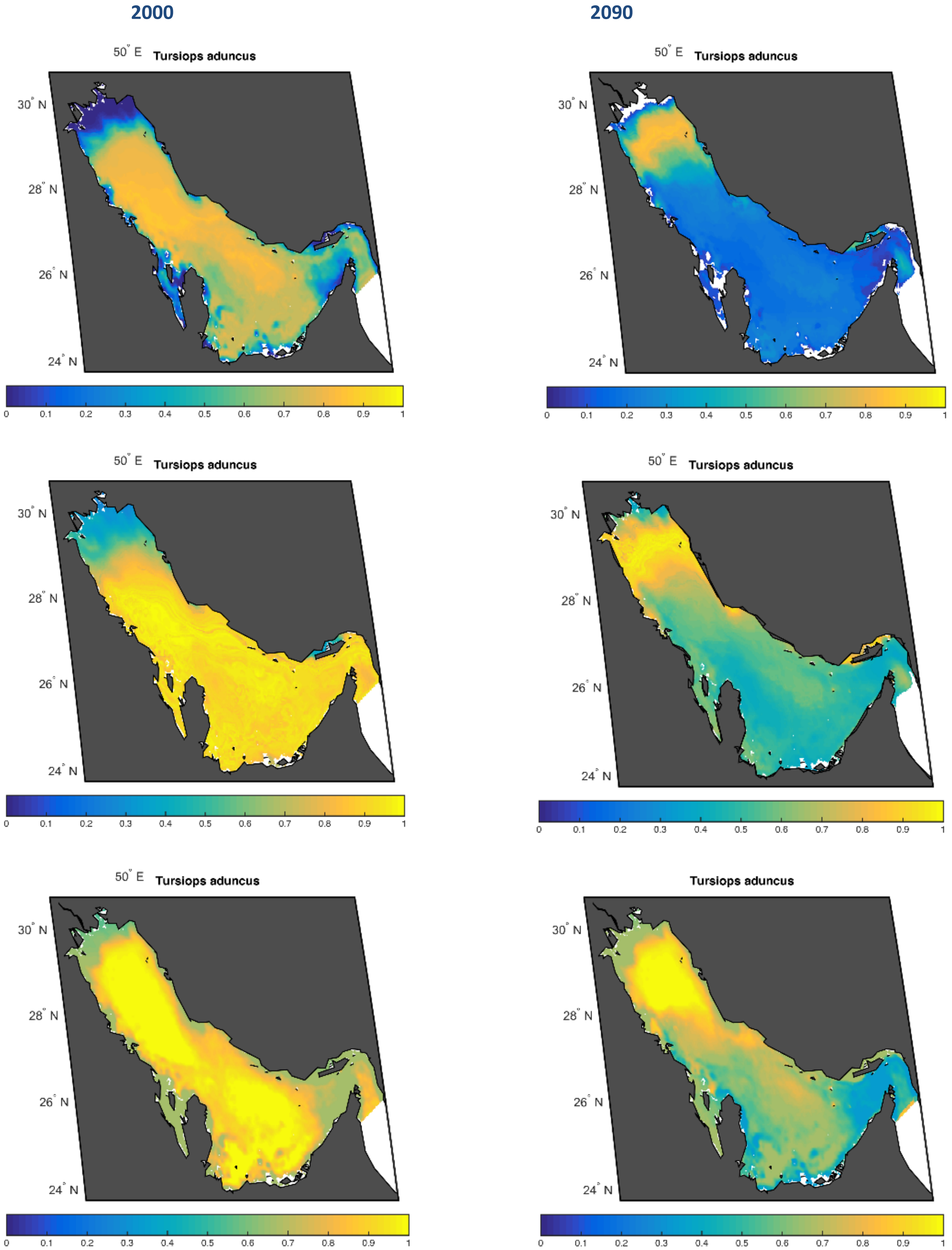


White areas indicate a probability of occurrence for the species equal to zero, therefore it is equivalent to loss of habitat

3.4.1. Bottlenose dolphin

All three environmental niche models project large declines in habitat suitability of bottlenose dolphin for most areas in the Gulf, with the exception of the northern region, under climate change (Figure 3-17). The pattern of changes is largely consistent among results from the three models. However, projected changes in habitat suitability from BIOCLIM by 2090 relative to 2010 under the RCP 8.5 scenario are more conservative, with a smaller decline in habitat suitability relative to projections from the other two models.

Figure 3-17: Projected 2010 (average of 2000-2020) and 2090 (average of 2080-2100) distributions of and habitat suitability for bottlenose dolphin in the Arabian Gulf under RCP 8.5 using NPPEN (upper), ENFA (middle) and BIOCLIM (lower). Habitat suitability for given species is scaled from 0 to 1, with 0 being not suitable and 1 most suitable.



White areas indicate a probability of occurrence for the species equal to zero, therefore it is equivalent to loss of habitat

3.4.2. Overall vulnerability of charismatic species

Overall, total habitat suitability of all charismatic species was projected to decline most in the waters of countries on the western side of the Gulf by 2050 and 2090 under RCP 8.5 (Figure 3-18). Habitat, as defined by changes in temperature and salinity, in waters of Oman, Bahrain and Qatar was projected to be particularly affected, with a 36% drop in future habitat suitability, followed by the UAE and Saudi Arabia. Waters of countries in the northern Gulf were projected to be less vulnerable. There is generally high agreement of results among the three environmental niche models (Figure 3-18).

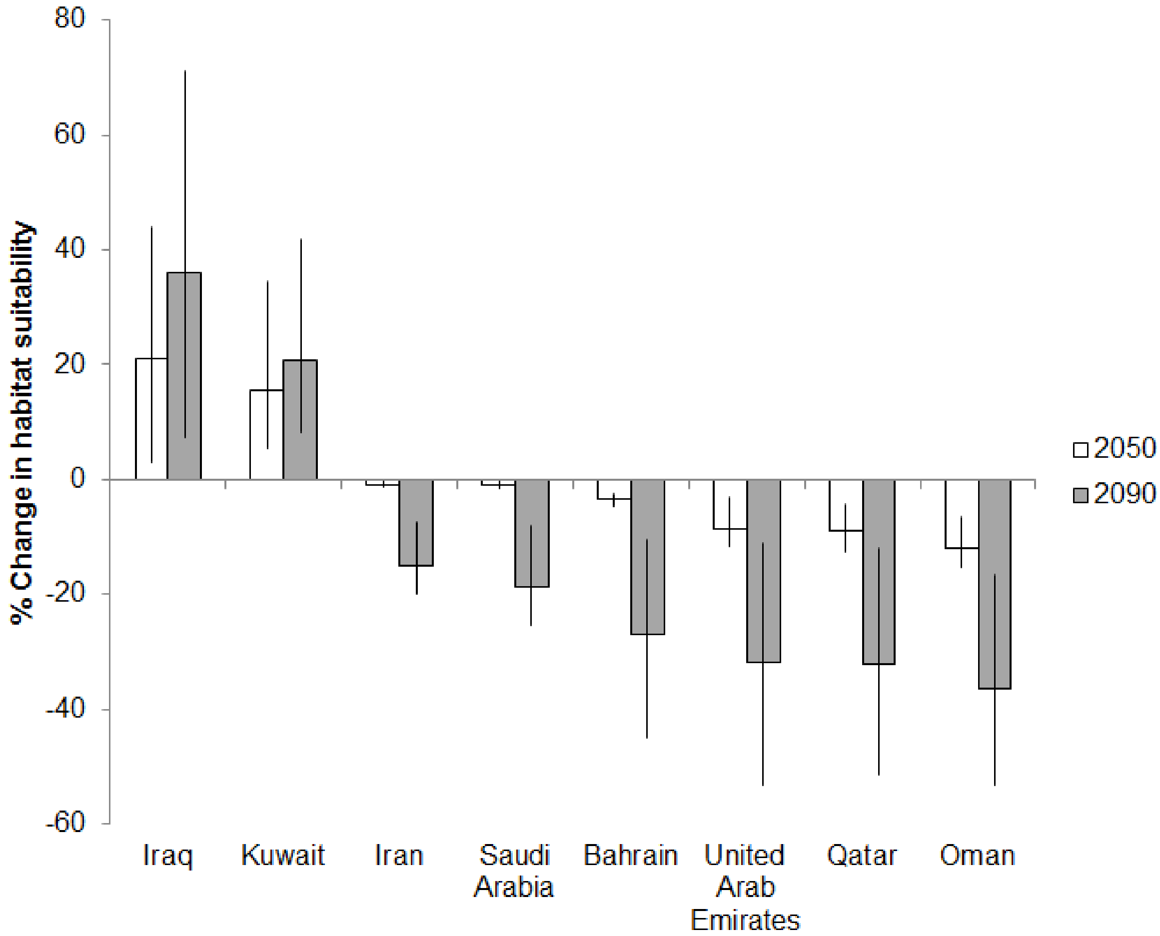


Figure 3-18: Change in habitat suitability for all charismatic species in the Economic Exclusive Zones (EEZs) of the Arabian Gulf in 2050 and 2090 under the RCP8.5 scenario, as an average across all three models. The error

3.5. Vulnerability of national economies to climate change impacts on fisheries

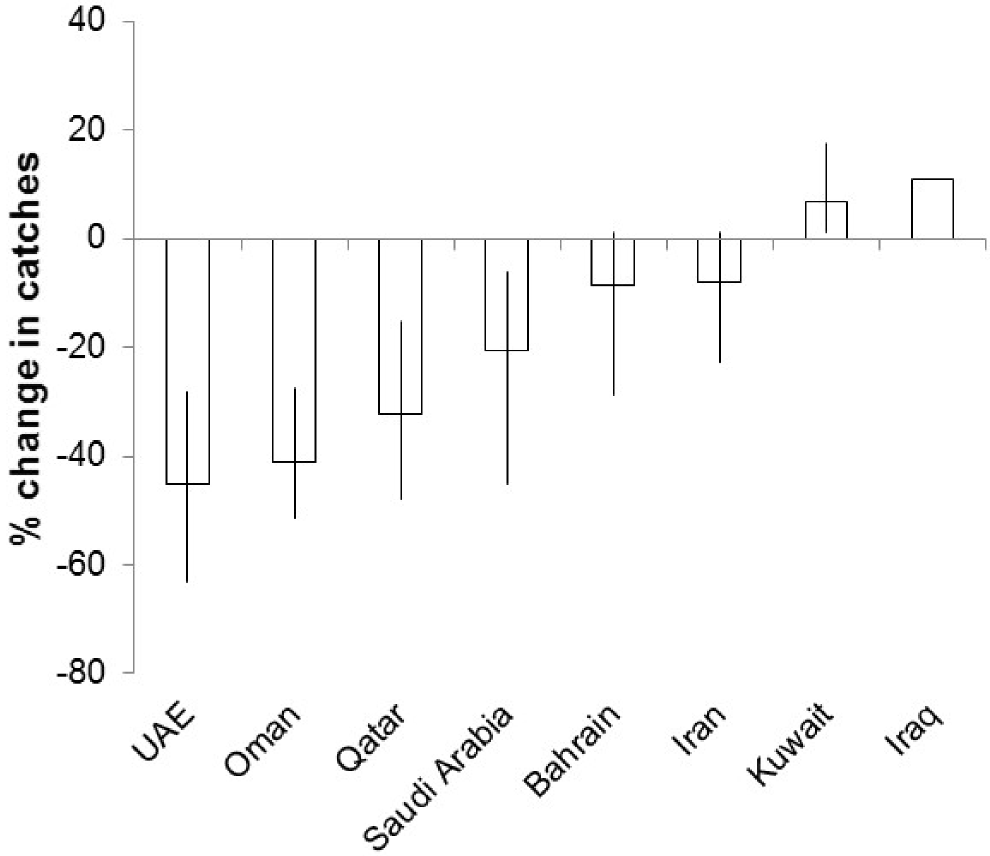


Figure 3-19: Change in catch potential in the Economic Exclusive Zones (EEZs) of the Arabian Gulf in 2090 under RCP8.5 scenario as predicted by an average of the BIOCLIM, NPPEN, and ENFA models. The error bars represent inter-model range.

While projections were slightly different between models, overall catch potential declined in several countries on the western side of the Arabian Gulf (Figure 3-19). Qatar, Oman and the UAE were particularly affected, with a drop of more than 30% in future commercial fish catch potential.

Results from the vulnerability assessment integrating changes in catch potential with socio-economic indicators showed Iran and Oman as most vulnerable to the impacts of climate change on fisheries. The UAE and Iraq were labelled of "medium vulnerability", while Kuwait and Saudi Arabia exhibited low vulnerability. For countries on the western side of the Gulf, Bahrain and Oman were the most vulnerable. Countries with high adverse impacts on future catch potential will likely come to rely more heavily on other forms of income generation and may need to devise alternate strategies for food security.

For both Oman and the UAE, vulnerability is mostly tied to the country's exposure to climate change impacts (i.e., reduced future fisheries). Although the UAE's economy is only slightly dependent on fisheries (~0.08% of GDP), the country is highly exposed to climate change impacts, therefore yielding a relatively high overall vulnerability score (0.49). While Iraq has very low adaptive capacity, its exposure to climate change is very low, yielding a medium score for overall vulnerability (0.45). Iran's fisheries ranked as the most vulnerable when

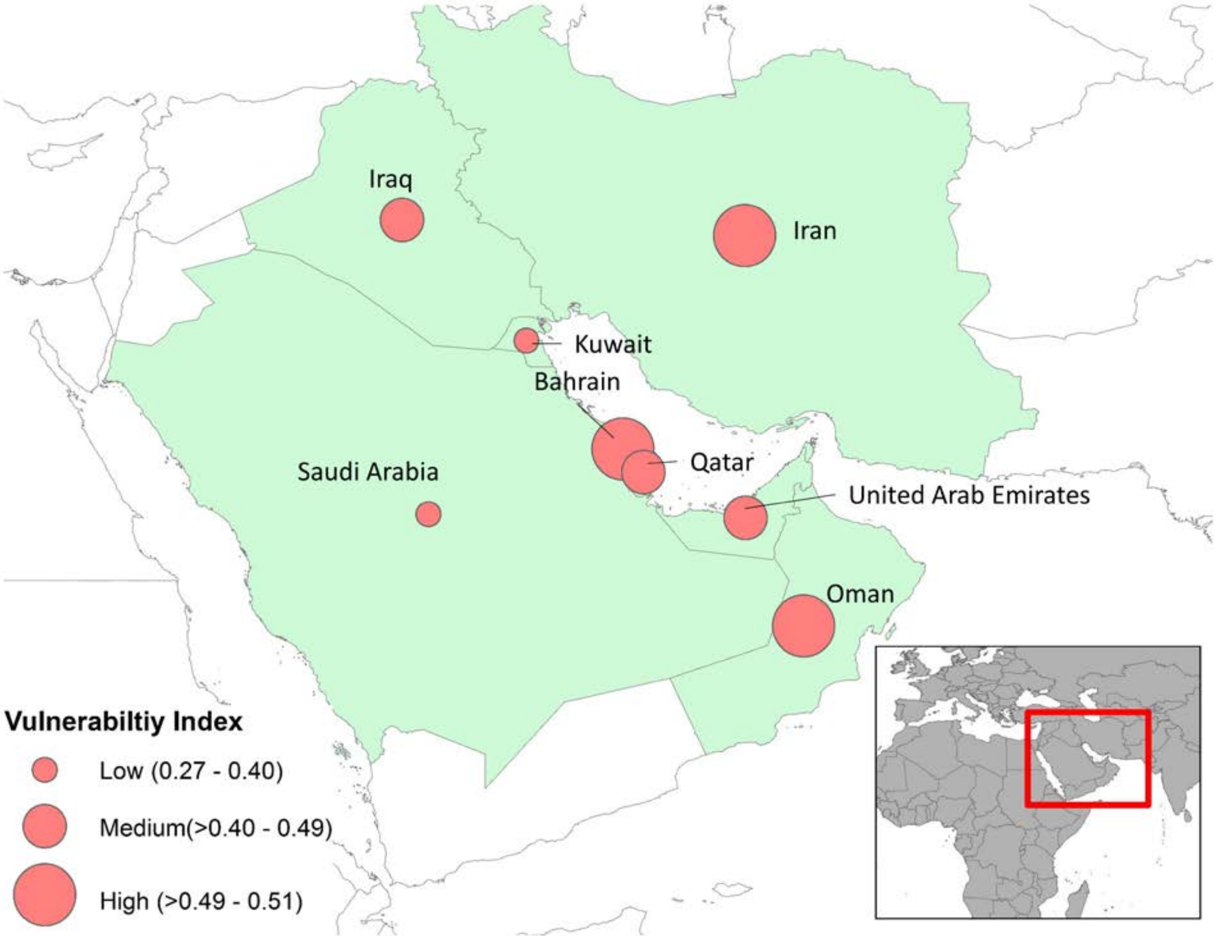


Figure 3-20: Relative vulnerability of national economies in 2090 due to climate change impacts on fisheries in the Arabian Gulf only, using the methodology presented. Note that for Saudi Arabia, Oman, and Iran, countries with fisheries in other seas beyond the Arabian Gulf, relevant variables in the vulnerability assessment were pro-rated to the proportion of total catches derived from the Arabian Gulf.

combining changes in catch potential with the nation's socio-economic framework (0.51).

While scoring relatively low for exposure, Iran ranked second highest for its sensitivity and second last for its adaptive capacity to climate change. This finding seems reasonable as Iran has the longest coastline in the Arabian Gulf, derives the highest catch, and has the least employment alternatives in the region.

A map of the fisheries vulnerability index for each country is shown in Figure 3-20 and listed by country in Table 3-1.

Table 3-1 - Relative vulnerabilities of national economies to climate change impacts on fisheries. Note that for Saudi Arabia, Oman, and Iran, countries with fisheries in other seas beyond the Arabian Gulf, relevant variables in the vulnerability assessment were pro-rated to the proportion of total catches derived from the Arabian Gulf.

Name	Exposure	Sensitivity	Adaptive capacity*	Vulnerability Index	Rank
Bahrain[1]	0.40 (5)	0.65 (1)	0.43 (5)	**0.49**	**3**
Iran	0.39 (6)	0.46 (2)	0.68 (2)	**0.51**	**1**
Iraq[2]	0.10 (8)	0.34 (4)	0.92 (1)	**0.45**	**5**
Kuwait[3]	0.16 (7)	0.18 (6)	0.47 (4)	**0.27**	**8**
Oman[4]	0.90 (2)	0.13 (8)	0.47 (3)	**0.50**	**2**
Qatar[5]	0.76 (3)	0.17 (7)	0.35 (7)	**0.43**	**6**
Saudi Arabia[6]	0.58 (4)	0.20 (5)	0.37 (6)	**0.39**	**7**
United Arab Emirates[7]	0.96 (1)	0.35 (3)	0.14 (8)	**0.49**	**4**

[1] Fish protein as proportion (%) of all animal protein and economic diversity values are missing for Bahrain;

[2] Number of fishers in the fisheries sector; number of people involved in fisheries relative to other economic sectors and economic diversity indices are missing for Iraq;

[3] Fisheries export value as proportion (%) of total export value and poverty rate indices are missing for Kuwait;

[4] Poverty rate values are missing for Oman;

[5] Fish protein as proportion (%) of all animal protein and poverty rate indices are missing for Qatar;

[6] Fish protein as proportion (%) of all animal protein and poverty rate indices are missing for Saudi Arabia;

[7] % of children under five who are underweight and school enrolment ratio indices are missing for the UAE.

* The higher the value of the adaptive capacity component, the less capacity of a country to adapt to climate change.

4. Discussion

4.1. Vulnerability of marine biodiversity and fisheries

Climate change is projected to have large impacts on marine biodiversity in the Arabian Gulf region. Impacts are predicted to be particularly high along the south and southwestern coasts, where high rates of local extinction are projected by the end of the 21st century. Overall, habitat suitability for all marine species included in this study (56 priority species identified on the basis of their importance to fisheries, their vulnerability according to IUCN, and selected in consultation with local stakeholders) is projected to undergo major declines. These findings imply that under climate change, as modelled in this study through changes in salinity and temperature, local extinction rates are expected to increase considerably throughout the Arabian Gulf.

At a global level, hydrological and biogeochemical conditions in the Gulf are considered highly specific. This area represents, for most of the environmental variables used to define the current environmental niche of species considered, the extreme end of the environmental gradient they inhabit (Hume *et al.* 2015; Hume *et al.* 2016). Consequently, most of the Arabian biodiversity pool can be classified into two distinct environmental types: 1. migrating species with a high tolerance to environmental variations (i.e., euryecious, particularly eurythermic species) and; 2. endemic or locally-adapted species with a wide environmental range, but highly adapted to the present environmental conditions in the Gulf (i.e., stenoecyous). The main hotspots of biodiversity are located along coasts, particularly in the south-eastern part of the Gulf and in specific regions where biogenic habitats such as coral reefs and seagrass are found (e.g., area around the Khark, Qehm or Bahrain Islands and nearby protected areas such as in Heleh, Mond, Jubail or Haraye Khmair).

Climate change is projected to have large impacts on marine biodiversity in the Arabian Gulf region. Impacts are predicted to be particularly high along the south and southwestern coasts, where high rates of local extinction are projected by the end of the 21st century. Overall, habitat suitability for all marine species included in this study (56 priority species identified on the basis of their importance to fisheries, their vulnerability according to IUCN, and selected in consultation with local stakeholders) is projected to undergo major declines.

Although this study focused on 56 of the 1000s of species occurring in the region, given the Arabian Gulf's unique extreme environmental conditions, and the level of adaptation displayed by many of its species, our findings regarding the general pattern of climate change impacts on marine biodiversity is likely to be applicable to many fishes and invertebrates in the Gulf. **Since most species are either highly adapted or at the edge of their environmental ranges, their sensitivity to any environmental or habitat perturbation is likely to be high. Thus, it is not surprising that projections of local species extinctions driven by temperature change are high.** Model results showed that under climate change, species' ranges would shift poleward, from the eastern part of the Gulf to the coast of Iraq and Iran by 2090. As species' northern expansion/range is limited by land, the scope for these to adapt to warming through a poleward range shift is limited. Such *cul-de-sac* effect would increase the overall rate of local extinctions in the Gulf and has been projected to occur in other semi-enclosed seas such as the Mediterranean (Ben Rais Lasram *et al.* 2010). Biodiversity losses due to climate change are likely to be exacerbated by other direct human impacts such as pollution, eutrophication, and coastal reclamation (Hamza and Munawar 2009; Sheppard *et al.* 2010; Naser 2014).

Results also showed that a decline in species habitat suitability translated directly into a projected decrease in maximum fisheries catch potential, particularly along the southwestern parts of the Gulf. We integrated these findings into a vulnerability assessment framework that included indicators for countries' socio-economic sensitivity and adaptive capacity. Findings from this assessment showed that the nations most vulnerable to climate change impacts on fisheries were not confined to the southwestern coast, but also included Iran and Iraq. By integrating the ecological results of climate change impacts on marine biodiversity into a more comprehensive socio-economic framework, this study's findings highlight the value of such an analysis (i) to better inform the adaptation process and (ii) to assist national economies and societies to better anticipate, and prepare for adaptive mechanisms to cope with, climate change impacts so that efforts can be focused and prioritized.

4.2. Robustness and uncertainty

4.2.1. Projecting climate change impacts on fishes and invertebrates

We evaluated the impacts of climate change based on modelled species-specific preferred ranges and drove projections using predicted temperature and salinity shifts. For marine fishes and invertebrates, temperature is a primary climate stressor that affects their physiology, distribution and phenology (Pauly 2010; Pörtner *et al.* 2013). However, other factors, such as oxygen concentration, acidification, and changes in ocean circulation can moderate a species response to temperature under climate change (Pauly 2010; Pörtner and Peck 2010; Cheung *et al.* 2011; Gattuso *et al.* 2015; Barton *et al.* 2016). The accuracy of projections is also contingent on the outputs from regional oceanographic models. The environmental niche models applied in this study assume that species' traits do not evolve as environmental conditions change, but species may well adapt to warming through genetic or transgenerational adaptations (e.g., Hume *et al.* 2016). However, the extent of such adaptive responses may be limited, as postulated from the substantially lower species diversity in the Arabian Gulf relative to the adjacent Indian Ocean where conditions are not as extreme. The time frame over which they would have to evolve given the pace at which climate change is advancing may also be too short. In addition, these projections do not include trophic interactions among species or how other human impacts such as changes in fishing effort may influence species' presence and distribution as well as biodiversity patterns.

Overall, the projected patterns of change in habitat suitability for marine fishes and invertebrates should provide useful indicators of climate change impacts on their diversity and meaningfully inform the development of adaptation strategies. The magnitude of these changes however is less certain.

4.2.2. Projecting climate change impacts on charismatic species

The results of this study suggest an increase in vulnerability of charismatic species to climate change in the Arabian Gulf. For hawksbill turtles for example, model projections based on changes in temperature and salinity relative to the species' environmental niche predict that habitat loss would be most significant in south and southwestern parts of the Gulf. Post-nesting tracks of 90 turtles showed these areas to currently be the most important for this species in the Arabian region (Pilcher *et al.* 2014). Marine mammals generally have wider tolerance windows for variations in sea temperature and salinity. Therefore, projected declines in habitat suitability for dugongs and dolphins may be overestimated. Overall, confidence in the projections of habitat suitability loss for charismatic species, as a result of future climate-mediated changes in temperature and salinity, is much lower than for other groups.

The approach utilized here did not include behavioural or other species characteristics that may make these species vulnerable to climate change stresses. For instance, sea turtles have a complex life history. Females lay eggs on their natal beaches, and hatchlings enter the oceans where they grow into juveniles on the high seas before recruiting to neritic habitats several years later. Sea turtles are highly migratory, travelling between foraging and nesting grounds that can sometimes be oceans apart (>3000 km). Some of these life stages may be more vulnerable to warming than others. Generally speaking, climate change is of concern for sea turtles because (Poloczanska *et al.* 2009; Hawkes *et al.* 2009; Fuentes *et al.* 2010; Witt *et al.* 2010):

- changes in ambient temperature may impact the sex ratio of embryos at nesting beaches (e.g., warming could potentially result in a shift in sex ratios towards females at many rookeries but see Pilcher *et al.* 2015) and fitness of hatchlings;
- rising sea levels and increased storm intensity will negatively impact available sea turtle nesting grounds. Around 1000 green turtle females nest annually on Karan and Jana Islands in Saudi Arabia (Pilcher 1999; Al-Merghani *et al.* 2000), and around ca. 500 hawksbill turtle females nest annually on Jana (Pilcher, 1999). Hawksbills also nest at several key sites in Iran (ca. 1000s of females/year) (Mobaraki, 2004), at numerous small islands in the United Arab Emirates (Pilcher *et al.* 2014), and at Fuwairit, Ras Laffan, and Halul in Qatar (Tayab and Quiton 2003). Green turtles nest in small numbers in the United Arab Emirates (Al-Suweidi *et al.* 2012); and both species also nest in small numbers on islands off Kuwait (Al Mohanna and George 2006; Rees *et al.* 2013); and
- changes in food availability may reduce their overall fitness and resilience.

In the case of sea turtles in the Arabian Gulf, overall, our modelling results show that changes in salinity and temperature may present stresses of relatively low concern to the sea turtles themselves (see also Pilcher *et al.* 2015), particularly when compared to other threats faced in the region (Sale *et al.* 2011). Nonetheless, a recent study in the Gulf has shown that a number of hawksbills travelling between nesting and foraging grounds when water temperatures are elevated undertook summer migration loops generally moving in a northeasterly direction toward deeper water, swam at greater speeds, and had trajectories that were significantly inversely correlated with temperature (Pilcher *et al.* 2014a). The authors conclude that Gulf hawksbills spend about 20% of their time undertaking these summer migration loops, a thermoregulatory response to avoid elevated sea surface temperatures and potentially physiology-threatening conditions. Continued increases in temperature may force turtles to extend such migrations and spend more time in deeper cooler waters, increasing their overall energy demand. These stresses likely would be compounded by the decline in health of their foraging grounds with the advent of climate change (Wilson *et al.* 2002), particularly for hawksbill turtles (Pilcher *et al.* 2015).

Other important factors that were not considered in the methodology described here and that may significantly affect marine turtle populations are:

- climate change impacts to nesting beaches (Fish *et al.* 2005, Fuentes *et al.* 2011) in the Arabian Gulf, for those individuals that use the region's coastline for reproduction. This segment of the population may also suffer from climate change impacts to its foraging grounds that may be within or outside of the Arabian Gulf. Green turtles nesting at Karan and Jana for example have been found foraging off the UAE and the bulk of that stock is likely to reside entirely within the Gulf (Pilcher *et al.* 2015); and
- climate change impacts to feeding grounds, specifically seagrass beds (Orth et al 2006, Waycott *et al.* 2009) for green sea turtles and coral reefs for hawksbill turtles, for those individuals that depend on the Arabian Gulf to forage. Model projections show *casi* no changes in the habitat suitability of *Halodule univervis*, major losses for *Halophila ovalis* around the UAE and the eastern coast of Qatar, and the total disappearance of *H. stipulacea*. Green turtles are known to predominantly forage on the former two, and based on projections, may in the future depend more heavily on *H. uninervis,* currently considered the most common species in the Gulf (Erftemeijer and Shauil 2012). Key foraging areas to date include seagrass beds in the UAE, Abu Dhabi in particular, as well as smaller areas in Qatar and Saudi Arabia (Pilcher *et al.* 2015). Future studies should endeavour to obtain more information on green turtle diets from the region to discern to what extent they depend on different seagrass species and/or algae as well as small benthic invertebrates for forage to help inform how predicted changes may impact turtle fitness in the future. This segment of the population may also suffer from climate change impacts to its nesting grounds that may or may not be in the Arabian Gulf.

Overall, the highly migratory nature of marine turtles, and their ability to move considerable distances in short periods of time, should increase their resilience to climate change. In the context of the Arabian Gulf, this may mean that turtles may come to spend less time in the region. However, any such resilience is likely to be severely compromised by other anthropogenic influences (e.g., bycatch fishing operations, loss of nesting and foraging habitat due to pollution, eutrophication and coastal development). This would also hold true for other charismatic species. For example, mapping of historical dugong sightings indicates that the population may have experienced a range contraction of up to 26%, with records found in Kuwait and Iran previously thought not to have dugongs (Al-Abdulrazzak 2015).

While dolphins and dugongs have less complicated life cycles than marine turtles, changes in their environment other than sea temperature, such as key forage species, are likely to be more significant in determining their vulnerability to climate change. For dugongs for example, we would expect impacts to their main source of forage, seagrass to be critical. Looking at projections for all three species of seagrass one may postulate that dugongs would focus their grazing activity on the rhizomes of the two main species, *H. ovalis* and *H. univervis*, and that their distribution may decline around the UAE and Qatar in response to declines in *H. ovalis*. Not surprisingly, the most important habitats for dugongs, whose population is the largest known outside Australia, occur around Murawah Island (UAE); between Qatar and Bahrain; and between Qatar and the UAE (Preen 2004). In turn, the vulnerability of seagrass to climate change is likely to depend on species' tolerance to changes in temperature and salinity (see above), but it is also arguably most dependent on changes in turbidity, sea level and UV-radiation for example. Light is a key environmental resource for the growth and survival of seagrass. Dredging, infilling and industrial developments, in addition to directly removing large areas of shallow productive benthic habitat, significantly affect turbidity and sedimentation and are considered the greatest threats to this important habitat (Erftemeijer and Lewis 2006; Erftemeijer and Shauil 2012). In the case of dolphins, their distribution may shift in accordance with changes in the habitat suitability of their key prey. Currently, very little is known about this species, with reports of population sizes reaching 1,200 (Preen 2004), but no absolute measure of abundance for anywhere in the region. Currently, the status of the species is unknown (Baldwin *et al.* 2004). To better assess the likely impacts of climate change on the species beyond projected temperature and salinity as undertaken here, future studies should aim to gain greater ecological understanding of this species in the Arabian Gulf and the risks to the species from different threats it is currently exposed to. It is likely that incidental capture in fishing nets, coastal and offshore development, pollution, boat traffic, oil and gas exploration, military exercises, and biotoxins associated with red tide events (Baldwin *et al.* 2004) may cause greater harm to the species, and thus be more important to mitigate, in the short and long term, than climate change.

For species such as sea turtles, dugong, or dolphins, the modelling approach outlined here presents interesting insights, with a number caveats. Future analyses should consider including changes in future primary production and combine these with changes in other ecological components important to their distribution (e.g., availability and quality of nesting and foraging grounds). Overall, it is important to note that vulnerability of large megafauna to climate change outcomes are likely to be quite variable and their prediction is therefore complex. Current efforts towards long-term monitoring; mix stock studies with in-water surveys; greater understanding of the importance of different areas/habitats for sea turtles and other marine fauna; cross-sector and cross-boundary collaboration between governments, universities and industries together with wide-scale stakeholder engagement; as well as the development of conservation strategies that combine protected areas and the regulation of fishing and shipping activities, are to be improved upon, supported and encouraged. The latter is particularly important given that charismatic species, particularly sea turtles and cetaceans (71% decline in cetacean abundance in the UAE between 1986 and 1999 (Preen 2004)), have suffered from significant anthropogenic impacts other than climate change and their curtailment is of key importance to the conservation of species in the region.

4.2.3. Assessing socio-economic vulnerability to climate change impacts

Although the framework used for assessing the vulnerability of national economies to climate change impacts on fisheries is relatively comprehensive, some caveats and shortcomings in the approach remain (see Annex VIII for details by indicator and for select variables). For example, the exposure dimension consists of one indicator (i.e., change in fisheries catch potential under climate change), while the other two dimensions are made up of several indicators. Therefore, the change in catch potential may be overrepresented in the overall vulnerability index. Moreover, because previous studies have shown results between different measures of vulnerability to be strongly correlated (e.g., Cinner *et al.* 2012) we chose to give each indicator within a given dimension and each dimension within the overall vulnerability index equal weighting. Based on local settings, stakeholders may wish to give individual variables and/or indicators different weightings.

Projected changes in fish catches will impact the supply of fish available for local consumption (i.e., food security) and exports (i.e., income generation). The magnitude of this impact will require a detailed analysis of overlap between affected fish species and exported fish, as well as countries' reliance on imported fish to meet local demand. While detailed considerations fall outside of the purview of this report, we suggest that national-level economic impacts are likely to be relatively minor, given that fisheries exports constitute less than 0.5% of total exports for all Gulf States. However, socio-economic impacts are likely to be comparatively greater at localized scales where there is direct and heavy reliance on fishing activities to support household incomes and where catch declines may therefore reduce the purchasing power of people to buy more nutritious food (hence affect food security). Based on these considerations, future studies may have to be focused on comprehensive economic analysis of food supply/demand and trade, specifically addressing:

- the direct impact of a reduction in catches on food security (and the local socio-economy); and
- the indirect impacts on food security and local economies of a reduction in catches.

Impacts are likely to be most severe for those economies that may need to increase imports even more because their own fisheries are suffering from climate change.

In the context of the socio-economic impacts of changes in landings to national economies it is important to remember that our analyses focused on the Gulf region. Some countries that had high vulnerability scores to climate change impacts (e.g., Oman, Saudi Arabia) may in reality be less exposed to climate change than results suggest based on catches obtained from, and climate change impacts on, another sea (alternatively based on future climate change projections for those marine areas, results may actually be worse).

While it would not be practical to make generalised statements on policy and adaptation recommendations for all countries, this study shows that certain countries have comparatively higher capacity to mitigate climate change impacts on fisheries than others. For instance, the UAE appear to have reliable fisheries management, economic complexity, and a governance structure that encourages transparency, political stability, and accountability. These factors are all essential requirements for the design, implementation, and long-term sustainability of climate change adaptation. Policies will have to tackle the impacts of anticipated fisheries decline, to which the UAE are highly exposed to, such as reduced fish supply, unemployment in the fishing and related sectors, and the downstream effects on other sectors of the economy. Another approach is to address areas that contribute to a country's high sensitivity ranking. For example, the physical well-being of coastal communities in Bahrain, and hence that also of its coastal fisheries, is most predisposed to the negative effects of future sea level rise given its high coastal dependence score. This suggests that precautionary actions should be taken to build infrastructure to make communities safe. Relevant agencies should also prepare fishing dependent households to deal with potential economic decline, through socio-economic development programmes such as financial planning education and skills diversification.

Overall, characterization of the level of vulnerability to climate change of a fisheries-based social-ecological system is an important first step, and our assessment provides a good general indication of the potential vulnerability at the national level. Vulnerability assessments for coastal communities to climate change impacts on fisheries would require more detailed, community-specific studies. For example, participatory-based assessments could factor in the more subjective dimension of vulnerability of communities to climate stresses, helping to ensure that results can be more closely linked to effective adaptation processes on the ground. This complementary methodology is also likely to have greater uptake and implementation potential. Ultimately, developing and strengthening a capacity to anticipate and act on change is fundamental (Allison *et al.* 2009).

4.3. Adaptation to climate change impacts on biodiversity

Marine biodiversity was found to be particularly vulnerable to climate change impacts along the south and southwestern coasts of the Gulf, and efforts should probably prioritise these areas. Multiple human stressors, such as habitat destruction and overfishing, are likely to exacerbate this vulnerability. Effective management of activities in the Arabian Gulf under climate change is likely to increase the resilience of ecosystems and the adaptive capacity of policy-making systems, for example by reducing other human perturbations, to ensure the sustainable flow of ecosystem services into the future. Impacts of climate change on marine biodiversity can be moderated by reducing stresses from overfishing and destructive fishing practices; habitat degradation; pollution and runoff; oil and gas exploration; land-use transformation, land reclamation and sedimentation; as well as invasive species. Therefore, effective implementation of ecosystem-based management that considers a much wider range of environmental and human stressors is fundamental to increasing the adaptive capacity of marine social-ecological systems to climate change. This includes strengthening the implementation and enforcement of current regulations and agreements to protect marine resources in the Arabian Gulf.

Adaptive marine conservation and management are important in uncertain future ocean ecosystems (Walters and Martell 2004). The reduced predictability of marine ecosystems due to climate change will make it more difficult to provide accurate assessments of the current and future status of marine biodiversity. Also, changing baseline oceanographic and ecological conditions may affect the effectiveness of existing conservation and management measures such as marine protected areas (MPAs). Monitoring programs that are designed for a changing ocean and that incorporate collected data as well as adapt to analyses' findings are thus critical to adaptive systems. Monitoring will include data for indicators at the pressure, state, and response levels, thereby promoting fast decision responses to changing and uncertain conditions and allowing a suite of possible responses to be maintained. However, the potential for mal-adaptation and trade-offs from multiple adaptation actions should be evaluated. For example, it is expected that the expansion of desalination facilities would increase the already high level of salinity in the Arabian Gulf, further exacerbating the impacts of climate change on marine species.

While MPAs certainly do not offer a panacea for climate change impacts on biodiversity and fisheries in the Gulf area, they are regarded as an important tool for the sustainable management and conservation of marine biodiversity, and have been shown to enhance population resilience to climate-driven disturbances. However, climate change induced changes in environmental suitability and resulting species' distribution shifts may lead to both emigration and immigration of species from or into an MPA (Micheli *et al.* 2012). It will be important to have a closer look at existing MPAs and what threats they face, to devise and implement measures to mitigate these, particularly for MPAs that emerge as critical in the future. Existing and proposed MPAs should be associated with comprehensive management plans for them to be effective. For example, our findings showed MPAs along the coast of Iran to likely experience species invasion as a result of climate change. While such findings may help in highlighting the importance of these areas and the need to strengthen their management regimes well into the future, the detailed consequences on the existing communities from such invasions is unknown. Climate change will alter the specific species assemblage being conserved, with the potential loss of species of conservation value and a reduction in the efficacy of the MPA. There is therefore a need to increase the robustness and enhance the resilience of protected areas themselves to climate change. For example, by assessing the degree of future environmental change within proposed protected areas, conservation planning may be used to protect against biodiversity loss (Levy and Ban 2013). Additional MPAs to develop national and regional networks of MPAs may also increase the likelihood of effectively conserving species following climate change-induced range shifts (McLeod *et al.* 2009; Gaines *et al.* 2010) and may offer some additional resilience.

The sooner precautionary measures directly targeting fisheries effort (particularly in countries most affected by changes in catch potential) that take into consideration future changes are taken, the smoother the transition will be. Such considerations should involve wide-scale local stakeholder involvement at all levels to raise awareness and empower communities to aid in proposing solutions to tackle the required changes. Reducing compounding stresses will also help further ensure the sustainable flow of ecosystem services into the future.

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