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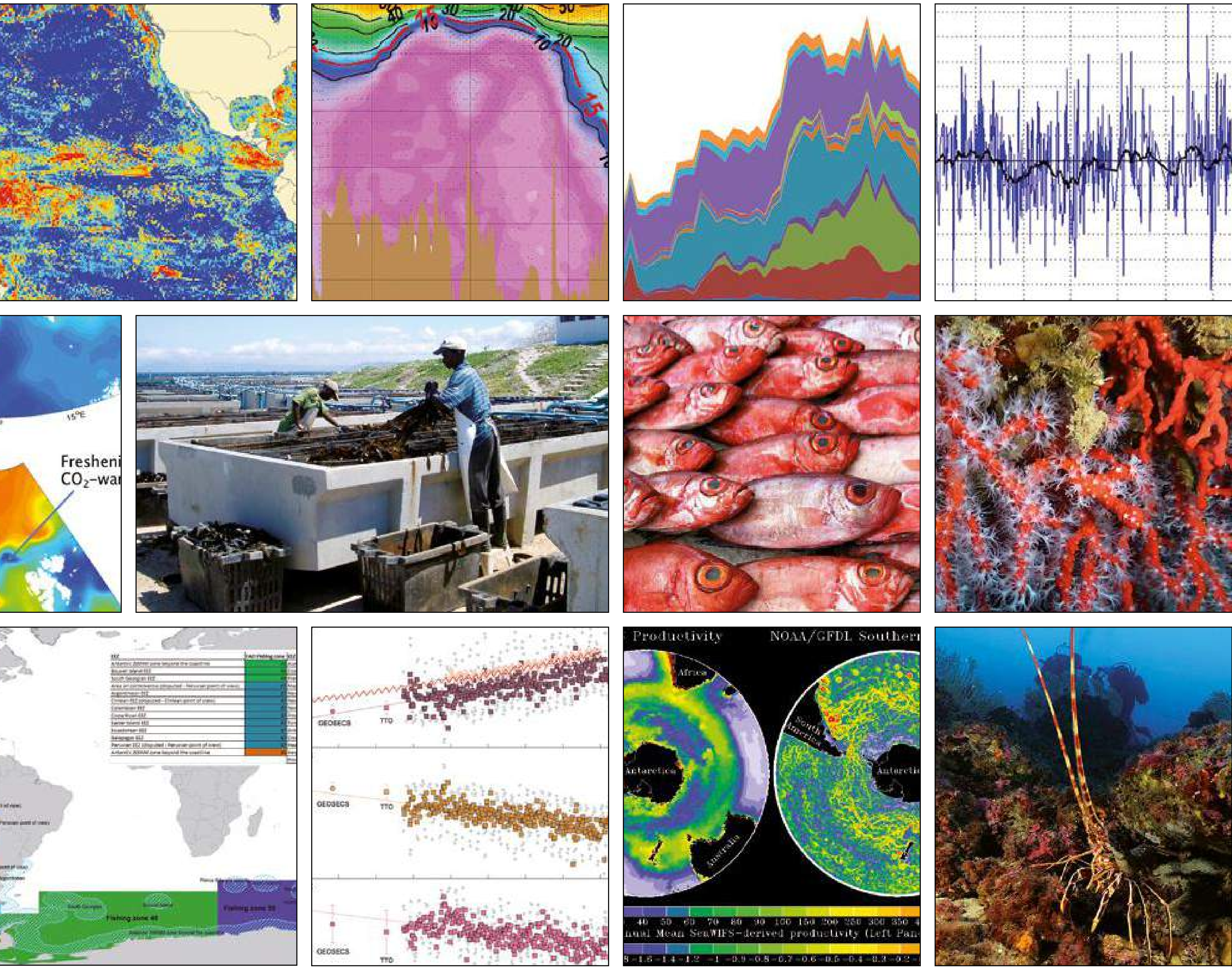
Bridging the Gap Between Ocean Acidification Impacts and Economic Valuation: Regional Impacts of Ocean Acidification on Fisheries and Aquaculture

Hilmi N., Allemand D., Kavanagh C., Laffoley D., Metian M., Osborn D., Reynaud S. (eds.)



CENTRE SCIENTIFIQUE DE MONACO

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Bridging the Gap Between Ocean Acidification Impacts and Economic Valuation: Regional Impacts of Ocean Acidification on Fisheries and Aquaculture

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Contents

FOREWORDS

INTRODUCTIONS

The Southern Ocean and South Pacific Region

North Atlantic and Arctic Ocean

Central and South Atlantic Region

Mediterranean and the Black Seas region

North and Central Pacific Ocean Region

Indian Ocean and Red Sea

About IUCN

IUCN, International Union for Conservation of Nature, helps the world find pragmatic solutions to our most pressing environment and development challenges.

IUCN's work focuses on valuing and conserving nature, ensuring effective and equitable governance of its use, and deploying nature-based solutions to global challenges in climate, food and development. IUCN supports scientific research, manages field projects all over the world, and brings governments, NGOs, the UN and companies together to develop policy, laws and best practice.

IUCN is the world's oldest and largest global environmental organization, with more than 1,200 government and NGO Members and almost 11,000 volunteer experts in some 160 countries. IUCN's work is supported by over 1,000 staff in 45 offices and hundreds of partners in public, NGO and private sectors around the world.

www.iucn.org

The Centre Scientifique de Monaco (CSM)

The Centre Scientifique de Monaco (CSM or Monaco Scientific Centre) is a Monegasque independent public institute founded in 1960 by Prince Rainier III in order to provide the Principality of Monaco with means to conduct in depth biological research and support action of government organizations and international agencies to protect and conserve marine life. The CSM is now located in new premises overlooking Port Hercules of Monaco. The CSM laboratories are made up of an area of about 2300 m^2 dedicated to a broad range of environmental research activities within a Marine Biology Department (coral physiology and coral ecophysiology teams, environmental economics), a Polar Biology Department (studying the capacity of populations of penguins to adapt to global changes through the study of functional mechanisms and microevolutionary processes) as well as a new department of Medical Biology, dedicated to cancer research and gene therapy.

For the last 25 years, the CSM has mainly been studying coastal ecosystems and more particularly the effect of global climate change and ocean acidification on tropical and temperate corals. The CSM research interests range from molecular biology to ecology through biochemistry and microscopy in order to study mechanisms of coral biomineralization and symbiosis. One of the major features of the Monegasque centre of research has been to develop coral culture and propagation methods under controlled conditions allowing researchers to work on living and healthy animals. The CSM cultures more than 60 species of tropical, temperate and cold-water (deep-sea) corals for experimental purposes in their dedicated facilities (5 large-10,000L aquaria, 5,000L-aquarium, five experimental rooms containing more than 70 30L-aquaria), allowing them to test the effects of various environmental parameters on coral biology.

Due to societal concerns related to ocean acidification, the CSM has ran an environmental economy program since 2009 which helps decision-makers and international organizations to study socio-economic impacts of ocean acidification.

Besides basic research, the Marine Biology Department in collaboration with the two other Departments of the CSM is also involved in various fields of applied research such as marine biotechnology, coral reef health monitoring, effects of climate change, use of bio-implants in medicine, jewellery and the discovery of new molecules for pharmacology and cosmetics.

For more information, visit our website: www.centrescientifique.mc

IAEA
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Environment
Laboratories

The IAEA Environment laboratories (IAEA-EL)

Established in Monaco in 1961 as part of the IAEA Department of Research and Isotopes, the International Laboratory of Marine Radioactivity was renamed in 1991 the Marine Environment Laboratories (IAEA-MEL) to reflect a broader scope of work involving the use of radioisotopes and stable isotopes to understand the complexity and fragility of marine environment. These laboratories remain the only marine laboratories within the UN system. In 2010, the IAEA Terrestrial Environment Laboratory in Seibersdorf, Austria joined IAEA-MEL that was subsequently renamed the IAEA-Environment Laboratories (IAEA-EL). In their early days, the laboratories were located on the premises of the Oceanographic Museum of Monaco however in 1988 the laboratories moved to the newer area of the Principality “Fontvieille” before finally moving to their current location on the Port Hercules of Monaco in 1998 where they are made up of 3,000 m2 of state-of-the-art environment studies technology.

For over 50 years, the IAEA Environment Laboratories have been developing and using nuclear and isotopic techniques to respond to requests on technical assistance and research for IAEA Member States through expert advice, training courses and technical cooperation projects and to provide technical backstopping to other UN agencies and programmes, e.g. UNEP, IOC-UNESCO, IMO, FAO, UNDP, WHO and WMO.

The IAEA-EL primary goal is to advance the peaceful use of nuclear techniques to understand, monitor and preserve the marine and terrestrial environment and its resources. For example, the IAEA-EL applies nuclear and related technologies to address problems associated with coastal zone management, impacts of climate and environmental change on biodiversity and socio-economic and safety impacts of pollution on living resources and their trade.

Through the unique diagnostic power of isotopes the IAEA-EL are committed to equipping new generations of scientists with knowledge and expertise on the processes governing the environment and the impacts of the factors threatening it such as pollution and climate change.

In recent years, several multinational and national research projects on ocean acidification have emerged significantly advancing the knowledge in this domain. In order to obtain the greatest value from these initial research investments and results, the establishment of an international coordination platform on ocean acidification was suggested by the SOLAS-IMBER Ocean Acidification Working Group and the international Ocean Acidification Reference User Group. In response to this recommendation and to the growing concern of IAEA Member States, the formation of the Ocean Acidification International Coordination Centre (OA-ICC) was officially announced by the IAEA in June 2012 at the Rio+20 UN Conference.

The OA-ICC is working to communicate, promote and facilitate global activities on ocean acidification. It will serve the scientific community and science users (policy makers, the general public, media and other stakeholders). Focusing on international activities which are not currently funded at national or international levels, its role is to support activities related to global actions on ocean acidification. These include international observation, joint platforms and facilities, collaboration between natural and social sciences, exchange between students and scientists, joint experiments, definition of best practices, open-access bibliographic database, data management, capacity building and dissemination.

For more information, visit our website: http://www.iaea.org/nael/page.php

Both institutes collaborate with the Association Monégasque pour l’Acidification des Océans (AMAO; Monegasque Association for Ocean Acidification) together with the Oceanographic Institute and The Prince Albert II Foundation. The goals of the AMAO are to communicate, promote and facilitate international actions on Ocean Acidification and other global stress factors affecting the marine environment.

For more information, visit AMAO website at http://www.fpa2.com

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ACRONYMS

AZA	Allocated Zones for Aquaculture
BATS	Bermuda Atlantic Time Series
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CCSBT	Commission for the Conservation of Southern Bluefin Tuna
CIESM	Mediterranean Science Commission
CMCC	Euro-Mediterranean Center on Climate Change
COLTO	Coalition of Legal Toothfish Operators
CPPS	Permanent Commission for the South Pacific
CWC	Cold Water Corals
DIC	Dissolved Inorganic Carbon
DWFN	Distant Water Fishing Nations
DWFNs	Distant Water Fishing Nations
EAF	Ecosystem Approach to Fisheries
EBSA	Ecologically or Biologically Significant Area
EEA	European Environment Agency
EEZ	Exclusive Economics Zones
ENSO	El Niño Southern Oscillation
ESTOC	European Station for Time Series in the Ocean
EU	European Union
FAD	Fish Aggregating Device
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GEOSECS	Geochemical Ocean Sections Study
GFCM	General Fisheries Commission
GHG	Green House Gas
GOBI	Global Ocean Biodiversity Initiative
HAB	Harmful Algal Bloom
HCS	Humboldt Current System
IATTC	Inter-American Tropical Tuna Commission
ICCAT	International Commission for the Conservation of Atlantic Tunas
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
ITF	Indonesian Throughflow
IUCN	International Union for the Conservation of Nature
IWC	International Whaling Commission
LME	Large Marine Ecosystem
NASA	National Aeronautics and Space Administration
NGO	Non-Governmental Organization
OA	Ocean Acidification
OECD	Organisation for Economic Co-operation and Development
OMZ	Oxygen Minimum Zone
PICTs	Pacific Island Countries and Territories
PPP	Purchasing Power Parity
RCP	Representative Concentration Pathways
RFMO	Regional Fisheries Management Organisation
S	Salinity
SEAFDEC	Southeast Asian Fisheries Development Center
SEC	South Equatorial Current
SIDs	Small Island Developing States
SME	Small and Medium sized Enterprises
SMR	Standard Metabolic Rate
SPRFMO	South Pacific Regional Fisheries Management Organisation
SST	Sea Surface Temperature
TA	Total Alkalinity
TAC	Total Allowable Catch
TTO	Transient Tracers in the Oceans
TC	Total Carbon
UNCLOS Seas	United Nations Convention on the Law of the
UNFCCC	United Nations Framework Convention on Climate Change
UNGA	United Nations General Assembly
UNWTO	United Nations World Tourism Association
VME	Vulnerable Marine Ecosystem
WCPFMC	Western Central Pacific Fisheries Management Commission
WCPO	Western and Central Pacific Ocean
WIO	Western Indian Ocean
WTP	Willingness to pay

FOREWORDS

Palais de Monaco

September 2014

I would like to quote my ancestor Prince Albert 1st: *"I wanted to give oceanography an international forum in keeping with the considerable importance of its role in the advancement of human knowledge and at the same time create a focal point where those serving Science, that is to say the truth, may join forces to find new weapons to combat the obstacles that ignorance and superstition have, in the past, along with the blindness of brutal revolutions, caused to proliferate in place of the advancement of thinking".*

This text written in 1912 is still relevant now, and today more than ever, I believe it is necessary to rally all disciplines to a common cause: the Oceans. The oceans do not just belong to one discipline but are the crucible of them all and all Nations should work together.

With this objective, specialists in Life Sciences and Humanities met at the Oceanographic Museum in Monaco to try to find practical solutions to the numerous problems Man has inflicted on his environment and for the resulting consequences.

This cooperation is one of the recommendations in the Monaco Declaration called for in my 2008 address and which was signed by 155 scientists from 26 countries.

This cross-disciplinary cooperation is sometimes rendered complex due to diverse working methods, different vocabulary or even by the suspicions that these disciplines arouse in each other, exacerbated by a priori assumptions or false truths peddled by some scientists who deny the long term environmental changes caused by Man.

The Scientific Centre of Monaco and the Environmental Laboratories of the International Atomic Energy Agency have helped to respond to this recommendation for joint cooperation. These two organisations, which are internationally recognised for their works on the study of the biological impact and more recently the socio-economic impact of the Acidification of the Oceans, were more than qualified to organise this workshop. It was fully supported by my Foundation and my Government as well as by the Oceanographic Institute which hosted the event and the French Minister of Ecology, Sustainable Development and Energy and by the American Department of State, all of whom I would like to thank here.

.../...

The first gathering of this workshop in 2010 produced concrete results. This second workshop was an opportunity to formulate new policy recommendations and to gain an overview of the sensitivity of different world oceans to acidification, highlighting both similarities and differences. This volume reiterates this and I would like to thank the IUCN for undertaking its publication.

Gone are the days when you could separate Man from Nature. Without proper management of natural resources, economic development prospects will be obstructed and poverty will extend further and further across humanity.

Whilst this link is already recognised for our land based environment as a result of the work of Sir Nicholas Stern, it is still in its early stages with regard to the marine environment.

We are so used to living with the sea that we no longer appreciate what it provides. As well as fishing and aquaculture which the experts have specifically studied during this workshop, the oceans also play a vital role in climate regulation, production of the oxygen we breathe, tourism, transport and as a source of raw materials.

If our lifestyles do not change the benefits we currently enjoy from the oceans will be affected by acidification, the impact of which is often magnified by global warming.

Whilst scientific data may not yet be sufficient to deliver crucial elements to political decision makers, waiting around isn't an option because today's inaction will impact on the quality of life for tomorrow's children.

The impact of the acidification of the oceans is observable right now as can be seen from the examples cited in this work. For example products from the sea constitute the major source of protein for a little over one billion of some of the planet's poorest people. Therefore it is clear that acidification of the oceans is not just a matter for environmental conservation but also a major political concern for the lives, health and well-being of humanity. This is consistent with the recommendations of the Rio+20 workshop on food security advocated by Monaco.

.../...

Ocean acidification has been ignored for a long time by scientists, but now, thanks to the work of a handful of researchers, it has become a true research subject. The second meeting "The Oceans in a High CO_2 World" was held in Monaco in 2008 and was attended by 250 researchers. The third meeting was held in Monterey in 2012 and there were 540! Several chapters of the last report from the Intergovernmental Panel on Climate Change address this issue for the first time. Nevertheless the socio-economic impact is yet to be assessed by the Monaco workshop dedicated to the "Economy of the Acidification of the Oceans".

Solutions will come from a reduction in carbon dioxide production whilst maintaining our modern world's energy supply. Solutions must also be local. Increasing the number of marine protected areas as advocated by my Foundation in partnership with the Oceanographic Institute as part of the Monaco Blue Initiative is an effective response to a global issue, as it is now shown that these environments facilitate the resilience of ecosystems.

I am counting on scientists to find solutions that will allow sustainable aquaculture with species resistant to the new pH conditions of sea water. I am counting on economists to give political decision makers the requisite compelling data to guide their decisions and explain them to the public. The experts' role is to highlight this information whilst being aware of the associated uncertainties and without being alarmist.

The green economy must now extend to the oceans with fresh awareness of the environmental issues and its multidisciplinary components.

Ocean acidification – the other CO_2 problem – may be defined as the global decrease in ocean pH due to the absorption of atmospheric carbon dioxide. Signed by 155 scientists in the wake of the Second Symposium on Ocean Acidification in 2008, the Monaco Declaration called for creating links between biologists and economists to assess the extent of the impact of ocean acidification, and the costs of action and inaction. To facilitate this, the first international workshop on the economics of ocean acidification, organized by the Centre Scientifique de Monaco and the International Atomic Energy Agency in 2010, allowed a multidisciplinary dialogue to open between natural scientists and economists. This workshop identified fisheries and aquaculture among the main economic sectors impacted by ocean acidification.

A second international workshop was held in November 2012 involving 55 experts from 19 countries along with representatives of international organizations. The workshop explored the level of risk, and the resilience or vulnerability of defined regions of the world ocean in terms of fishery and aquaculture species and economic impacts, and social adaptation. The workshop sought to address common themes or specific priorities for action by communities, resource managers and policymakers. The goal was to integrate scientific and economic knowledge and perspectives on fishery related ocean acidification issues.

The workshop highlighted that communication and interactions among participants of various backgrounds of economics, ecology, fisheries, and aquaculture are essential to meet the objective of providing clear, concise policy recommendations concerning human adaptation and mitigation of impacts of ocean acidification. Strengths and vulnerabilities in terms of species and ecosystems, as well as, coastal communities and industries must be assessed to the greatest extent possible within the areal boundaries. The challenge is to combine the topics of ocean biogeochemistry, marine biology and ecology, seafood supply and harvest, fisher activities and dependencies, economy and governance.

The findings and recommendations of the respective regional working groups are provided in this report: The main conclusions of the workshop include:

- All parts of the ocean are not equal with respect to physico-chemical and socio-economic impacts of acidification on fisheries and aquaculture;
- Marine species have different sensitivities to ocean acidification;
- Ocean acidification could exacerbate the effects of other environmental pressures, such as increased temperature. It may also inhibit or facilitate the development of certain species, inducing a change in the composition of ecosystems;
- The full cost of ocean acidification is undetermined, but probably undervalued. Some estimates suggest a cost of $10 billion per year on world fisheries, with direct impacts to the economy of coastal areas, which will represent 50% of the population by 2050;
- To cope with the socio-economic consequences of this phenomenon, human communities dependent on fishing or aquaculture will need to adapt their practices and environmental management;
- Finding aquaculture species tolerant to ocean acidification has been suggested as an adaptation practice.

Beginning at the workshop, and during the period since, regionally specific working groups have explored:

- Types of fisheries and aquaculture (industrial, artisanal, traditional, etc.) and their relative importance and value in ocean regions;
- Important biological, ecological, and economic components of fisheries;
- Varying perceptions of fishery and aquaculture sectors at global, regional and national levels; from the fish farmer to the commercial fishing fleet;
- Response strategies of aquaculture, industrial and traditional fisheries;
- Informational needs and expectations of the natural scientists, economists, managers and policymakers to address potential ocean acidification impacts;
- Future challenges for fisheries and aquaculture from analysis of current main issues of fisheries stakeholders (communities, industries, commercial entities, resource managers);
- Factors that may be important given future changes in markets, technology, demographics, and governance;
- Actions needed to incorporate ocean acidification in resource management plans at local, regional, national, and international levels, and to incorporate sustainable environmental policies into more general economic policies.

This document is the result of this interdisciplinary survey of ocean acidification-sensitive fisheries and aquaculture.

The Editorial Board

Nathalie Hilmi, Denis Allemand, Christopher Kavanagh,
Dan Laffoley, Marc Metian, David Osborn,
Stephanie Reynaud.

INTRODUCTIONS

A short summary of the current knowledge on ocean acidification

Jean-Pierre Gattuso [1, 2]

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1- INTRODUCTION

The oceans have absorbed between 24% and 33% of anthropogenic carbon dioxide (CO_2) emissions during the past five decades (Le Quéré *et al.,* 2009). While this uptake provides a valuable service to human societies by moderating the rate and severity of climate change, it comes at a cost for the oceans. The massive input of CO_2 generates sweeping changes in the chemistry of seawater, especially on the carbonate system. These changes are collectively referred to as "ocean acidification" because increased CO_2 lowers seawater pH (i.e. increases its acidity).

Ocean acidification, "the other CO_2 problem" (Doney *et al.,* 2009), has recently emerged as one of the largest threats to marine organisms and ecosystems (reviewed in Gattuso & Hansson, 2011). Describing and quantifying the plausible consequences of ocean acidification on societies, however, remains a challenge. Those consequences will depend on interactions among and between species and ecosystems (all reacting at different rates and magnitudes), on the interaction of ocean acidification with other ocean stressors (Bopp *et al.,* 2013), and on responses of each human group affected. Nevertheless, it is clear that the speed and magnitude of acidification is threatening many marine species and ecosystems. Calcifying organisms such as coral reefs, shellfish and zooplankton are among the first potential victims. Therefore ocean acidification will also impact various economic sectors (e.g. fisheries, aquaculture, tourism; see Cooley & Doney, 2009; Narita *et al.,* 2012) and coastal communities, and may also have major indirect effects on much broader segments of the world economy and population.

Ocean acidification appeared on the research agenda about two decades ago (Smith & Buddemeier, 1992; Gattuso *et al.,* 1998). It is now an important focal issue for the research community (Monaco Declaration 2009) and related societies (e.g. European Geosciences Union 2008; European Science Foundation 2009; Interacademy Panel on International Issues 2009).

2- CAUSES OF OCEAN ACIDIFICATION

There are two main causes of ocean acidification. By far the primary cause is the ocean's uptake of atmospheric CO_2, and there is growing evidence for secondary enhancement of CO_2-driven acidification by other pollutants in coastal regions (Cai *et al.,* 2011; Sunda & Cai, 2012).

2.1- Uptake of atmospheric CO_2

Rising atmospheric CO_2 is the major driver of ocean acidification globally. The increase of CO_2 in the surface ocean resulting from the uptake of anthropogenic CO_2 profoundly affects the seawater carbonate system through well-known chemical reactions. It lowers pH (increases acidity), increases the concentration of bicarbonate ions (HCO_3^-), decreases the availability of carbonate ions (CO_3^{2-}) and lowers the saturation state of the major shell-forming carbonate minerals such as calcite and aragonite. This process is known as "ocean acidification" because, even though the surface waters remain alkaline, seawater pH is decreasing.

Average surface water pH values[1] are in an accelerating decline: it was 8.3 during the last glacial maximum, 8.18 just prior to the industrial era, and 8.10 at present. Measured trends agree with those expected from the atmospheric CO_2 increase, with uncertainties larger for the high latitudes, deep ocean, coastal areas, and marginal seas. The basic chemistry of ocean acidification being well understood, future projections are quite reliable for the surface open ocean for a given atmospheric CO_2 trajectory (Orr, 2011). Those based on the International Panel on Climate Change (IPCC) scenarios give reductions in average global surface pH of between 0.14 and 0.35 units over the 21st century, which means surface pH may reach 7.8 in the year 2100 (Orr, 2011).

Despite anthropogenic CO_2 emissions being the primary driver of acidification, the chemical and biological impacts of ocean acidification would continue to intensify for many years thereafter even if emissions were halted altogether by the end of this century (Joos *et al.,* 2011). Nevertheless, mitigating CO_2 emissions would substantially ease the trajectory of acidification over the course of the 21st century (Joos *et al.,* 2011).

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[1] pH is expressed on the total scale throughout this report.

2.2- Coastal acidification due to inputs from land

Several anthropogenic inputs also exacerbate the effects of ocean acidification at smaller spatial scales (Feely *et al.,* 2010; Cai *et al.,* 2011). These inputs act disproportionately along coastal margins where anthropogenic stressors are most acute and where oceanographic patterns such as upwelling or incomplete flushing occur, especially in bays and estuaries.

Mechanisms for this locally-intensified acidification are known: while Hunter *et al.* (2011) show a negligible effect of deposition of atmospheric NOx and SOx, nitrogen and phosphate runoff from agricultural, industrial, urban and domestic sources causes eutrophication, triggering population spikes of algae or heterotrophic plankton (Cai *et al.,* 2011). When algal blooms are over, the organic matter decays, generating CO_2 and acidifying seawater. Understanding and mitigating these secondary causes of acidification is possible at the local and regional scales.

3- IMPACTS OF OCEAN ACIDIFICATION ON MARINE ORGANISMS AND ECOSYSTEMS

Ocean acidification can have a wide range of biological effects, through two main mechanisms. First, pH plays a key role in several physiological processes and many intracellular enzymes that control cellular physiology are pH-sensitive. The pH of body fluids in animals and the intracellular pH of various organs or unicellular organisms are tightly regulated, but regulatory mechanisms are energetically expensive and can be overwhelmed. The second mechanism occurs through changes in the concentration of molecules that are themselves substrates in key physiological processes. For example, carbon dioxide and bicarbonate are used in photosynthesis and carbonate is a building block of shells and skeletons made of calcium carbonate. Hence, ocean acidification can stimulate primary production since the concentrations of both CO_2 and HCO_3^- are larger at lower pH (see Riebesell & Tortell, 2011). It also often decreases calcification (the construction of shells and skeletons; Andersson *et al.,* 2011; Riebesell & Tortell, 2011), and stimulates nitrogen fixation in some cyanobacteria (Riebesell & Tortell, 2011). This suggests that highly calcium-carbonate-dependent ecosystems — such as coral reefs and oyster and mussel beds — could be particularly vulnerable.

However, the magnitude of species-specific physiological effects is highly variable and, in few cases, even the sign of the response may vary (Kroeker *et al.,* 2010, 2013). For example, there is evidence that the same species may differ in sensitivity among life stages (e.g., with enhanced sensitivity among larval stages; Kurihara *et al.,* 2008), among different strains of the same species (Langer *et al.,* 2009; Parker *et al.,* 2011), and dependent on their previous exposure (e.g., carry-over effects; Hettinger *et al.,* 2012; Parker *et al.,* 2012).

A recent analysis of the rapidly expanding body of research on acidification reveals consistent reductions in calcification, growth, and development of a range of calcified marine organisms despite the variability in their biology (e.g., morphology and life history strategies; Kroeker *et al.,* 2013). It also suggests that some taxa may be predictably more resilient to or may benefit from ocean acidification (e.g. brachyuran crustaceans, fish, fleshy algae, and diatoms). The study of Kroeker *et al.* (2013) did not consider all kind of effects. For example, neurological effects with repercussions for their behavior (Nilsson *et al.,* 2012) or the loss of phenolic compounds used as herbivore deterrents by fleshy algae (Arnold *et al.,* 2012). Furthermore, the potential for acclimation (Evans & Hofmann, 2012) or adaptation (Sunday *et al.,* 2010; Lohbeck *et al.,* 2012) in response to acidification could lessen negative effects. This remains a critical area for future research. While physiological effects on these calcified organisms can result in decreases in their abundance, the higher variability of species responses in multi-species studies indicates that species interactions will also be important determinants of abundance (Fabricius *et al.,* 2011; Kroeker *et al.,* 2011). Furthermore, understanding whether the remaining variation within taxonomic groups and life stages represents real biological differences among species, locally-adapted populations, or acclimatory capacities, or experimental error, remains a critical area for future research. Finally, marine organisms of the future will not be subjected to ocean acidification in isolation, and continued research on the concurrent effects of ocean warming and acidification is necessary to forecast the status of marine organisms and communities in the near-future.

4- KNOWLEDGE GAPS

Despite very active research on ocean acidification and the considerable increase in the number of papers, there are several key knowledge gaps preventing to assess the full extent of the impacts of ocean acidification with reasonable certainty.

- **Research needs to be scaled up.** Most information available on the impacts of ocean acidification was gained on isolated organisms on short periods of time. Little is known on the responses of whole ecosystems, on the impacts of multiple stressors, and on the potential for evolutionary adaptation. These limitations restrict the level of confidence of future projections.
- **Effects of ocean acidification on biogeochemical cycles at a global scale are uncertain**. Changing ecosystem composition and the oceans' carbonate chemistry affects biogeochemical cycles in complex ways. Ocean acidification may also affect production of climate-related gases. We need to understand ecosystem responses to the effects of ocean acidification in order to improve how global models simulate and predict biogeochemical changes.
- **Fish and fisheries.** It is uncertain how the effects on phytoplankton and zooplankton will propagate through the food web to affect fish and fisheries. Also, very little is known about the direct effects of ocean acidification on fish that are the target of commercial and subsistence fishing.
- **Socio-economic impacts** are expected but the size of the costs is uncertain.

ACKNOWLEDGEMENTS

This short summary is largely based on the following book and papers: Gattuso & Hansson (2011), Billé *et al.* (2013), Kroeker *et al.* (2013), and IGBP, IOC, SCOR (2013). Interested readers should refer to these references for further information. The support of the BNP Paribas Foundation and the European Community's Seventh Framework Programme (FP7/2007–2013) through the "Mediterranean Sea acidification in a changing climate" project (MedSeA) is gratefully acknowledged.

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Ecological effects of ocean acidification

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Ocean acidification is the ongoing decrease in the pH of the Earth's oceans, caused by the uptake of anthropogenic carbon dioxide (CO_2) from the atmosphere. The chemical process through which carbon dioxide results in ocean acidification is well understood and the fact that OA is occurring is not contested. We already know that the oceans' acidity has increased 30% since the industrial revolution, and projections under business as usual scenarios are that this rate will increase to 100-150% by 2100. The impacts of ocean acidification on individuals, populations and biological communities, however, are not well understood. This presentation was intended to provide a review of the literature in order to extract a number of messages that could be considered and debated in the regionally focused discussions:

— In considering the impacts of ocean acidification one has to note that the variability of pH in the world's oceans is comparable to the variability in sea surface temperature, with very significant geographical differences between oceans, and between inshore and offshore regions, and thus geographical differences in the impacts of ocean acidification are to be expected.

— These impacts will affect biochemical and cellular processes, which will cascade into organism, and likely into population and ecosystem processes. Most importantly, these effects will **interact** with effects that cascade from other forcings (e.g. ocean warming, deoxygenation, etc.) in complex manners.

— At species level it is expected that each species will demonstrate its own 'average' intrinsic resistance to ocean acidification and associated chemical changes. For example, cyanobacteria are generally thought to benefit from CO_2 increases, while diatoms are more likely to be outcompeted.

— As a result of the diverse metabolic changes at species level, differential dominance patterns are to be expected, and perhaps fundamental functional responses, albeit not **necessarily** total ecosystem productivity or total biomass.

— The overall impacts of ocean acidification exposure will ultimately depend on the combination of other forcings operating at the ecosystem level. There are expectations of significant synergistic, additive and antagonistic responses. As these are likely to be dynamic, impact assessments at community level remain elusive except perhaps for very direct responses on specific processes (e.g. calcification).

— In general, metazoans appear to be less vulnerable to ocean acidification than protozoans, as they buffer ocean acidification through their extracellular fluid.

— Calcareous species are more likely to be replaced by non-calcareous species as a result of ocean acidification, but competition, predation and other ecosystem processes are likely to be significant in determining overall responses.

— There are several metadata analysis on ocean acidification impacts on metazoans, but this are difficult to interpret, because experiments are generally not comparable, and because most exposure experiments report responses to shock rather than sensitivity to ocean acidification. This is changing, with more long-term experiments being conducted.

— There is increasing understanding of the genetic processes linked to CO_2 exposure, with genes up/down-regulated with significant differences in response between species (linked to life history), and within species. These genetic processes further highlight the difficulty of estimating ocean acidification effects on ecosystem production and diversity.

— Looking at the geological record for comparable periods and at the biological responses to change indicate that even for calcareous organism impacts are not uniform and that no two-ocean acidification events are the same. The role of synergistic environmental factors appears to be crucial.

— Attempts to model the ecosystem impacts of ocean acidification largely reflect deterministic parameterisation. These models have so far noted that temperature-driven changes in species distributions are potentially more significant than ocean acidification impacts alone.

- Research suggests that it is still too early to know if genetic variability among populations will result in ocean acidification selecting specific strains resistant to this forcing.
- Evolutionary adaptation to ocean acidification is to be expected, but there are concerns that ocean acidification will outpace adaptation. Research indicates that evolutionary adaptation does not depend on life span but evolutionary rates.
- The economic impact of ocean acidification is not well estimated, but local impacts (e.g. oyster farms in Oregon, USA) have been observed.

Based on the above messages, which are not comprehensive or complete, the speaker indicates a number of important areas of suggested future research:

1. Long-term experimentation under single and particularly multiple (often synergistic) stressors.
2. Investigations on genetic diversity and natural selection of strains, as well as on the processes of evolutionary adaptation.
3. Modelling efforts that focus not on the overall species effects of ocean acidification but on effects to specific metabolic processes including a degree of plasticity of individual response.
4. Long-term observation networks, both in the open ocean and coastal stations, and in vulnerable environments (e.g. coral reefs, upwelling zones, semi-enclosed seas, etc.).

Ocean acidification will continue for at least hundreds of years. Understanding the ocean under acidic conditions is an urgent and crucial endeavour. In researching impacts on ecosystem production, structure, dynamics, and on the resources provided by these ecosystems, the scientific community needs to recognise the complexities involved. There are situations and ecosystems (e.g. coral reefs) where complexities are significantly reduced, but these examples are not common. To extrapolate cell, organism, population, and ecosystem impacts to economic and social consequences, with a significant degree of confidence, is likely to be elusive for some time to come. An exception is impact to local and specific industries, where a single process (e.g. larval mortality) may push industries below particular profit thresholds.

Ocean acidification impacts on fisheries and aquaculture

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The presentation describes the global trends in fisheries and aquaculture, the threats to production and the threats to fisheries and concludes with a review of the challenges facing fisheries and the ocean acidification 'agenda'.

Recorded marine capture fisheries production reached a plateau in the 1990s and has varied in the range of 80-85 million tons per year since then. Global production has been maintained partly by the retention of fish that was previously discarded and is now frequently used for aquaculture feed. The top ten fish products are all finfish and represent 30% of all marine catches. These are mostly pelagic species (such as, anchovy, mackerel, pollock) harvested in the world's major upwelling systems and on the major continental shelves. Inland capture fishery production is relatively flat at about 10-11 million tons per year. Substantial additional quantities of fish are caught for subsistence consumption or simply remain unrecorded, or under-reported.

Aquaculture production is growing at over 8% per year and is the world's fastest growing food sector with production of over 63 million tons. Marine aquaculture, or mariculture, accounts for 30% of production and China accounts for over 60% of global aquaculture production. Finfish accounts for about 50% of production, seaweeds for about 25% and other groups such as shrimp, oysters and other shellfish and invertebrates account for the remaining 25%. There is direct market competition between capture and culture finfish products (such as tilapia, cod, salmon, catfish, hake, pollock), and for shrimp and other shellfish (such as oysters and mussels).

There are about 35 million commercial fishers and about 120 million people are directly dependent on capture fisheries. About 96% of these people are in developing countries (116 million) and over 90% capture fisheries workers are involved in small-scale fisheries. About 50% of the fisheries workforce is female and about 50% of the workforce is employed in inland fisheries. Large-scale fisheries land more fish, but small-scale fisheries produce more fish for domestic human consumption. The annual contribution of commercial fisheries to GDP is an estimated $274 billion and additional social and economic benefits accrue from subsistence and recreational fisheries.

About 50% of all marine stocks are overexploited. However robust stock assessments are generally only available for OECD countries and many developing countries lack the capacity to make robust assessments. The costs of catching fish tends to increase as fuel prices increase, as fish becomes increasingly scarce and as fishers respond by increasing investment in more efficient fishing technologies. A further response is to fish deeper and target lower and more productive trophic levels. Increased demand and population pressure is driving the increasing overfishing and on balance the trend in commercial fish biomass, stocks, and stock value is negative with an estimated annual loss of economic rents (potential net value of catches) in the order of $50 billion in 2005.

There is a range of success stories in rebuilding fish stocks and capture fishery productivity. These are generally based on governance reforms, often with co-management arrangements and more effective tenure and fishing rights arrangements to generate incentives for fishers to rebuild and sustainably use the fish stocks. While many of these success stories are in developed countries, community co-management has proved effective in several developing countries. Trade and emerging consumer preferences for sustainably certified fish products are also driving improved management of fisheries. Integrated coastal aqua farms are expanding, particularly in China, where fish cages, bivalve, seaweed and bottom feeders, such as sea cucumbers filter rich coastal runoff. The farms exist in a form of 'symbiosis' as they depend on urban waste water and fertilizer runoff for their productivity while 'cleaning' the effluents and reducing eutrophication and coastal marine pollution. Seaweed farms are likely to benefit from climate change and ocean acidification. Long-term investments by global energy companies in production of biofuels from microalgae could see major development of plant aquaculture. An estimated 60% of the supply of fish products for human consumption will be met by aquaculture. Latin America and China are projected to dominate net exports, while challenges related to aquaculture intensification, disease and feed supply will continue to emerge.

In addition to the threat of ocean acidification, rising ocean temperatures, overfishing and destructive fishing, fisheries production faces several other threats. These include habitat loss (particularly of wetlands, reefs, and seagrass bed), land-based sources of pollution, including siltation, effluents from extractive industries (mining, offshore oil & gas), invasive species and the pole-ward 'migration' of tropical species. Inland fisheries are threatened by water abstraction, dams, saltwater intrusion and pollution.

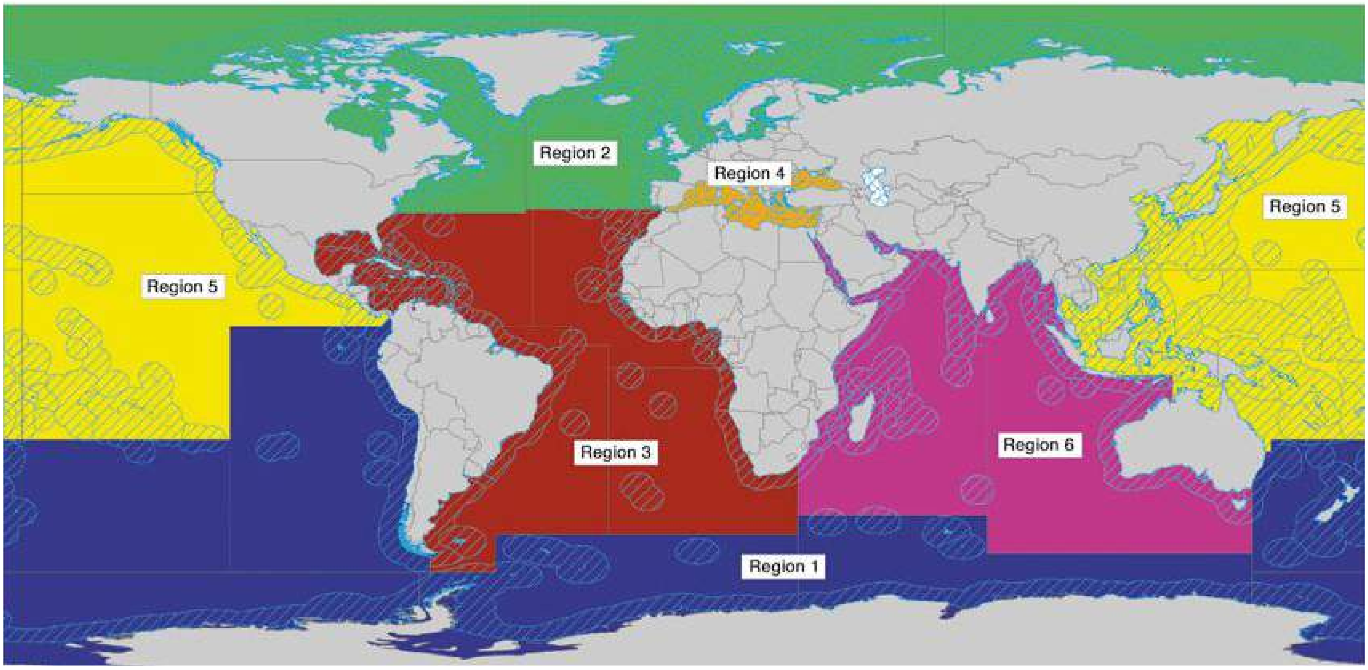
Current knowledge is insufficient to quantify the impact of ocean acidification on fisheries. This exercise will require knowledge of the impacts for major commercial species at different stages in their life cycles, understanding of the impacts on food chains and predator/prey relationships. Calibrating the impact of ocean acidification will also require consideration of the compounding effect of other stressors including rising ocean temperatures, or the spread of low oxygen zones. Key focal areas for research could include the impact on pelagic fisheries as the major contributors to global fish production; future coral reef fishery scenarios, as these systems support the livelihoods of some 500m people; species adaptation/substitution possibilities; exploring whether local mitigation measures are possible (for example, using seaweeds). It may also be possible to characterise ocean acidification impacts in relation to LMEs or oceanographic characteristics such as enclosed seas, upwelling or temperate and tropical shelf areas.

In terms of process, it will be useful to consider if ocean acidification knowledge can be organized around manageable, specified targets, such as the input to the IPCC, energy companies (algae), climate change adaptation priorities (such as for the island nations – SIDS). Should the 'ocean acidification agenda' work as an integral part of a global climate change agenda, or does the ocean acidification 'agenda' require a specific coordinating mechanism, financing, and political constituency? How can responsibility for the ocean acidification agenda be assigned, and how can the agenda be 'managed'? Can priority, targeted actions be identified and specific support enlisted through declarations and statements by international fora such as G20 and UNGA? In order to have traction an 'ocean acidification agenda' will need to build the business case for priority actions (other than reduction of GHG emissions); link ocean acidification to the poverty and sustainable growth agendas; target major concerns, such as jobs and food security.

In conclusion, it will be necessary to identify key action orientated knowledge investments, to build scientific consensus on key 'unknowns' trends, the orders of magnitude and the underlying assumptions. The uncertainties will need to be quantified and means to reduce the uncertainties identified and the consensus science represented more strongly in IPCC and similar initiatives. It will be useful to identify priority adaptation actions, their costs, and costs of inaction, and who pays these costs. Similarly it will be of value to identify strategic pathways to build awareness and political support for priority actions by developing 'champions' at national and international levels, possibly by identify the countries and interest groups most impacted by ocean acidification.

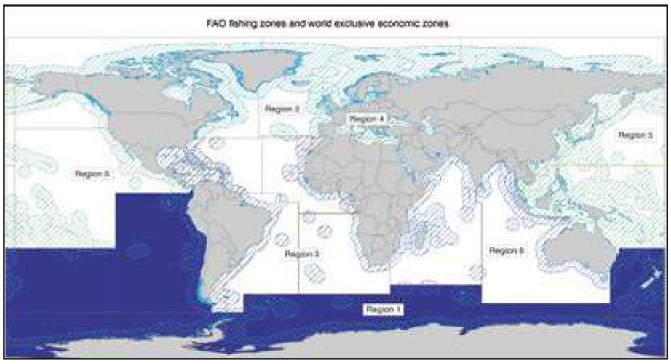
BRIDGING THE GAP BETWEEN OCEAN ACIDIFICATION IMPACTS AND ECONOMIC VALUATION

FAO fishing zones and world exclusive economic zones



The Southern Ocean and South Pacific Region

(FAO 81, 87, 88, 58, 48)



**Kieran Kelleher[1], Pierre Failler[1], Gilles Boeuf,
Leigh Gurney, Dan Laffoley, Laura Parker, Gretta Pecl,
Carol Turley and Michel Warnau[2].**

[1] Group leader. [2] Facilitator.

See map in Annex 1, p. 130.

EXECUTIVE SUMMARY

The Region comprises three sub-regions (FAO Statistical Areas) with very different characteristics. The South Pacific includes the vast and virtually unpopulated Southern Ocean surrounding the Antarctic. It has the world's largest fisheries off Peru and Chile and some of the world's best managed fisheries in Australia and New Zealand. The Region has over 27% of the world's ocean area and over 98% of the Region's total area of 91 million km^2 is 'open ocean'. The Region contains less than 5% of the global continental shelf area and only a fraction of this area is covered by three large marine ecosystems (the New Zealand Shelf, the Humboldt Current and the Antarctic large marine ecosystems (LMEs). The Humboldt Current System (HCS) is the world's largest upwelling which provides nutrients for the world's largest fisheries. The Region also has a high number of seamounts.

The marine capture fisheries of the Region produce over 13 million tons annually and an expanding aquaculture industry produces over 1.5 million tons. Peru's anchoveta fishery provides about half the world's supply of fish meal and oil, key ingredients of animal and fish feeds. El Niño Southern Oscillations (ENSOs), known more generally as El Niños, can substantially change the species composition of the key small pelagic catches (anchovy, sardine, horse mackerel and jack mackerel) causing production to fluctuate from about 4-8 million tons. Partly due to the lack of upwelling and shelf areas, fisheries production in the Southern Ocean and Area 81 is relatively small but supports economically important commercial and recreational fisheries and aquaculture in New Zealand and in New South Wales (Australia). Krill remains a major underexploited resource, but is also a keystone species in the Antarctic food web. The Region is home to numerous endangered species of whales, seals and seabirds and has a high number of seamounts, vulnerable ecosystems fished for high-value species such as orange roughy.

The fisheries and ecosystems of the Region are highly vulnerable to ocean acidification (OA), particularly when associated with the stresses from ocean warming and low oxygen. OA is likely to have negative impacts in the Region, but some opportunities may also arise for culture of seaweeds, or expansion of fisheries for species with higher resilience to OA. Other stresses include commercial fishing, ocean warming, and pollution. As the Southern Ocean and the HCS are areas where OA will have substantial and early impacts, a strong case can be made for the Region to invest in the science of OA and to pilot adaptation and mitigation measures.

Given the economic importance of fisheries in the Region, countries have well-developed fisheries management regimes and a strong marine science capability. The limited number of major industrial fisheries enterprises also suggests opportunities for broad stakeholder dialogue and engagement. Regional fisheries bodies have espoused an ecosystem approach to fisheries which creates the opportunity to include OA considerations in the preparation of scientific advice and the decision-making process.

The long term priority is to move towards reduction in GHG emissions and the Region can play an important role in pursuing an 'OA agenda' in international fora. In the medium term, the Region can envisage a range of actions to mitigate and adapt to the effects of OA. These include actions to enhance knowledge of the impacts and piloting policies and strategies for conservation and sustainable use of marine resources that take account of the impacts of OA. Raising stakeholder and public awareness will be an important step in generating initiatives, financing OA knowledge management and research and developing OA engagement strategies for the Region's capture fisheries and aquaculture. 'Technical' questions arising in the Region include the impact of OA on the Southern Ocean keystone species – krill; the impact of the combined stressors of OA and low oxygen in the Humboldt Current System; the need to increase understanding of the adaptive capacity of cultured molluscs to OA; and the need for expanded data on OA trends throughout the vast Region. Addressing these and other questions will contribute to the understanding of the economics of ocean acidification in the Region.

1. THE SPECIFICITIES OF THE REGION

The Southern Ocean and South Pacific Region are comprised of three sub-regions (FAO Areas) with very different characteristics. The Region includes the vast and virtually unpopulated Southern Ocean, the world's largest fisheries off Peru and Chile and some of the world's best managed fisheries in Australia and New Zealand. The Region is highly vulnerable to ocean acidification (OA), ocean warming and low oxygen, provides lessons in governance and the limited number of key actors provide basis for dialogue and action. While ocean acidification is likely to have primarily negative impacts in the Region, some opportunities may also arise. Targeted actions could be considered on knowledge management and research, management of capture fisheries and aquaculture and ocean acidification engagement strategies.

1.1. Geography

This chapter focuses on three distinctly different ocean areas comprising five FAO Fisheries Areas (the major geographical units used by FAO to group fisheries statistics). These are: the Southern Ocean (FAO Areas 48, 58, 88) surrounding Antarctica, considered as a single area for the purposes of this report; the Southwest Pacific (FAO Area 81), centred around New Zealand; and the Southeast Pacific (FAO Area 87), dominated by Peru and Chile. The areas are illustrated in figure 1.

There are few similarities between these areas. Peru and Chile are home to the world's largest single-species fisheries, dominated by anchovy and other small pelagic species. These fisheries are heavily influenced by the world's largest upwelling system and changing oceanographic conditions, in particular the decadal oscillation, El Niño. In contrast, Area 81 is the FAO area which consistently reports the lowest catches, attributable partly to the small shelf areas, low population and challenges posed by fishing remote ocean areas. The Southern Ocean is a vast but relatively fragile ecosystem particularly vulnerable to climatic change, with negligible population and low but expanding fishery production.

Despite the Region's vast area, only a fraction of this area is covered by three large marine ecosystems (LMEs; the New Zealand Shelf, the Humboldt Current and the Antarctic LMEs), suggesting massive 'open system' drivers of ocean processes, compared to the relatively more 'discrete' drivers in LMEs. The Region's oceanic area is over 98% of the Region's total area (91 million km^2), which covers over 27% of the world's oceans. However, the Region contains less than 5% of the global continental shelf area.

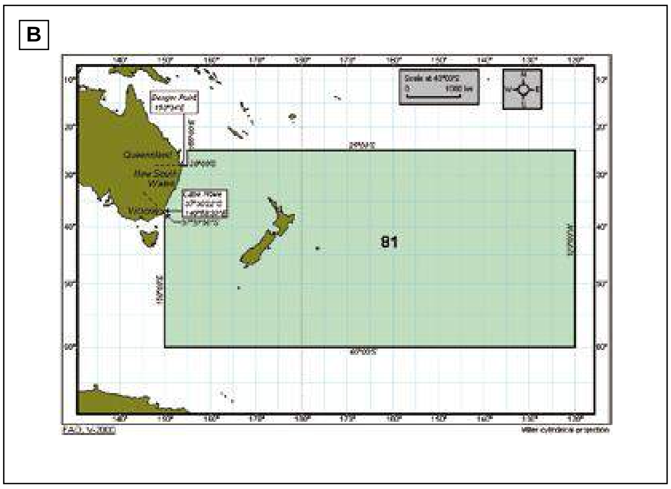
Figure 1.

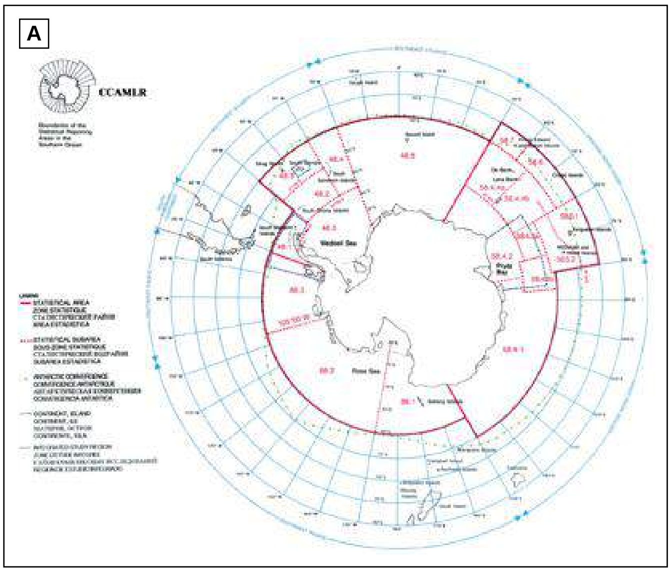
The South Pacific Region and Southern Ocean showing the five FAO Statistical Areas.

A) FAO Areas 48, 58, 88
http://archive.ccamlr.org/pu/E/conv/maplge.htm

B) FAO Area 81
http://www.fao.org/fishery/area/Area81/en

C) FAO Area 87
http://www.fao.org/fishery/area/Area87/en





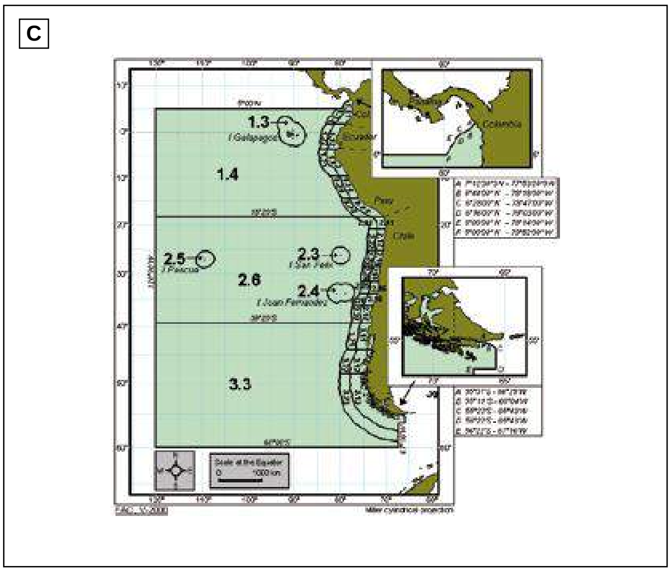


Table 1.

Surface area of FAO Areas 81, 87 and the three Southern Ocean areas (in km^2)

In km^2	Total area	Continental shelf	Oceanic area
Southern Ocean FAO Areas 48, 58, 88	33.97	0.52	33.45
FAO Area 81	27.66	0.41	27.25
FAO Area 87	30.80	0.57	30.23
Total	92.42	1.50	90.92
% of global	27.8%	4.7%	25.8%

Source FAO.

Coral reefs exist in the Region. They occur, for example, along the coast of Columbia and the Northern Island of New Zealand. However, as coral reef fisheries are discussed extensively in other chapters, the impact of ocean acidification on these fisheries is not addressed here.

1.2. Overview of fisheries production

The Region has some of the world's major fisheries, including the world's largest – Peru's anchoveta fishery. Chile also has major fisheries for mackerels, anchovy and squid and important coastal aquaculture. The anchoveta fishery provides about half the world's supply of fish meal and oil, key ingredients of animal and fish feeds. Production varies from about 4-8 million tons in response to ocean temperatures with decadal intrusions of warm tropical waters reducing productivity of the Humboldt Current ecosystem. These events, referred to as El Niños, or more accurately as El Niño Southern Oscillations (ENSOs) can substantially change the species composition of the key small pelagic catches (anchovy, sardine, horse mackerel and jack mackerel).

In contrast to the export driven fisheries of Chile, Peru and Ecuador, the relatively narrow shelf areas off New South Wales[1] (Australia) means that production generally supplies the local markets. New Zealand is a significant producer and exporter of hoki, squid, and shellfish. Extensive offshore deepwater plateaus around New Zealand have fostered important fisheries for Orange roughy, alfonsino and other deepwater species. However, difficulties in managing these fragile deepwater and seamount resources have resulted in declines in the catches of these species. Although production is dominated by industrial fisheries, small scale fisheries are socially and economically important throughout the Region, particularly in Latin America. Recreational fisheries are important in New South Wales and in tourist destinations throughout the Region.

All the countries[2] in the Region have an expanding aquaculture industry. Chile is the world's second largest producer of salmon. New Zealand and Australia also produce salmon (not in NSW). New Zealand is a large producer of green mussels. Most countries produce oysters and scallops with Chile becoming a global player in shellfish aquaculture.

The Southern Ocean has a relatively modest production in the order of 200,000 tons annually[3]. However species such as Patagonian toothfish and mackerel icefish are among the world's most high priced fish. Only a fraction of the total allowable catch (TAC) for krill (3.7 million tons; Figure 2) is harvested. New technologies are being introduced to profitably harvest krill, one of the few major global fish resources which remains substantially underexploited[4]. Krill is primarily used as a high-value fish feed, but an expanding range of pharmaceuticals and food additives are being developed from krill.

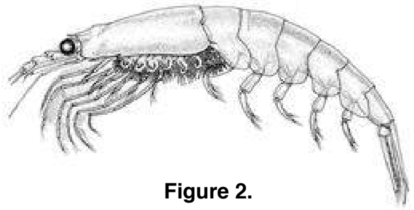


Figure 2.
Krill, *Euphausia superba.*

The Region provides a range of lessons on fisheries governance. Australia's fisheries management plans provide useful lessons on applying an ecosystem approach[5] and the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has pursued an ecosystem approach for several decades in managing the fisheries of the Southern Ocean. An ecosystem approach to fisheries (EAF) strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties of the biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries. New Zealand's fisheries are well known for a strong economic approach and well-developed rights-based approach. The economic approach to fisheries management focuses on generating economic returns and maintaining the wealth and capital value of fisheries. A rights-based approach draws on the idea that stronger tenure over fisheries resources creates incentives for better management; and where the fishing rights are tradeable, overcapacity will tend to exit the fishery as vessel operators sell their fishing rights. Peru has introduced a range of reforms greatly improving the profitability of the anchoveta

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[1] Note that effectively only New South Wales is part of Area 81.

[2] The main countries are as follows: Australia, New Zealand, Columbia, Ecuador, Peru and Chile. Other countries have overseas possessions, territories or islands in the region (i.e. the three FAO areas combined), where aquaculture can be considered negligible. These countries include: France, UK and South Africa.

[3] Commission for the Conservation of Antarctic Marine Living Resources recorded catches.

[4] Nicol, S. & Y. Endo, 1997.

[5] FAO Fisheries Departmentm 2003.

fishery. Chile has recently taken steps to reform its aquaculture governance following a collapse in the salmon farming industry.

A range of regional fisheries bodies illustrates various cooperation modalities. These include the South Pacific Regional Fisheries Management Organisation (SPRFMO), responsible for high seas resources, excluding tuna; the Western Central Pacific Fisheries Management Commission (WCPFMC), responsible for management of tuna in the Western Pacific; the Inter-American Tropical Tuna Commission (IATTC, responsible for tuna in the Eastern Pacific); the Permanent Commission for the South Pacific (CPPS, responsible for maritime policy in the Southeastern Pacific); and CCAMLR (responsible for management of Antarctic fisheries and other living marine resources, excluding whales and southern bluefin tuna)[6]. Non-governmental organisations also play a role in the conservation and management of the Region. These include Coalition of Legal Toothfish Operators (COLTO) and Birdlife, one of many organizations focused on conservation of albatross and other birds threatened by fisheries and changing ecosystems.

Figures 3 and 4 illustrate the trends in the catches of the top five species and the trends in production of the top five cultured species dominated by anchoveta and salmon respectively. The production trends are dominated by two features. In the case of capture fisheries, it is the influence of El Niño and fishing pressure on the anchoveta fisheries in Peru and Chile. In the case of aquaculture it is the collapse of the salmon industry in Chile (now recovering), due directly to disease and indirectly to weak environmental governance of the industry. The fisheries are of major importance in both Peru and Chile and of considerable socioeconomic importance in New Zealand.

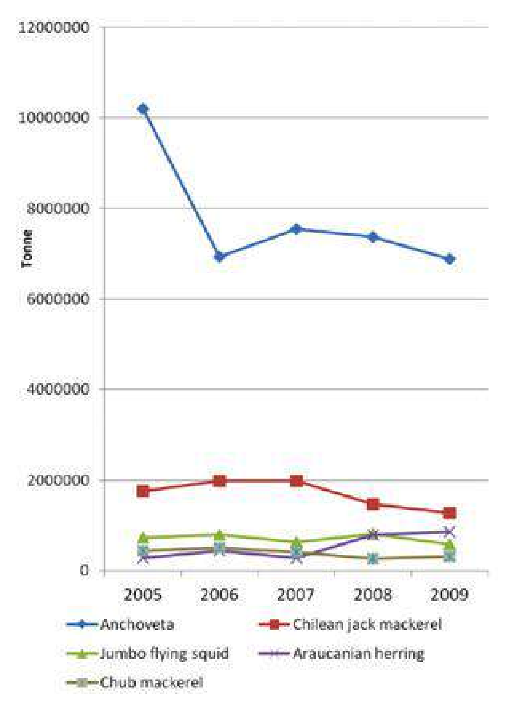
1.3. Main stressors

The fisheries of the Region are subject to multiple stressors including: fishing, ocean acidification, changing sea temperatures, salinity and dissolved oxygen. Fisheries production is also subject to the substantial variability of the upwelling of the Humboldt and other currents and their interplay with El Niño's and other climate-driven forces. While the impact of individual stressors can often be projected or modelled, the current understanding of the combined impact of multiple stressors is poor.

1.3.1. Ocean Acidification

Ocean acidification poses severe potential threats to Southern Ocean ecosystems[7] in particular. The relative undersaturation of calcium carbonate ($CaCO_3$) in the Southern Ocean means that ocean acidification is likely to have its greatest initial impacts there if the level of atmospheric CO_2 continues on its projected trajectory.

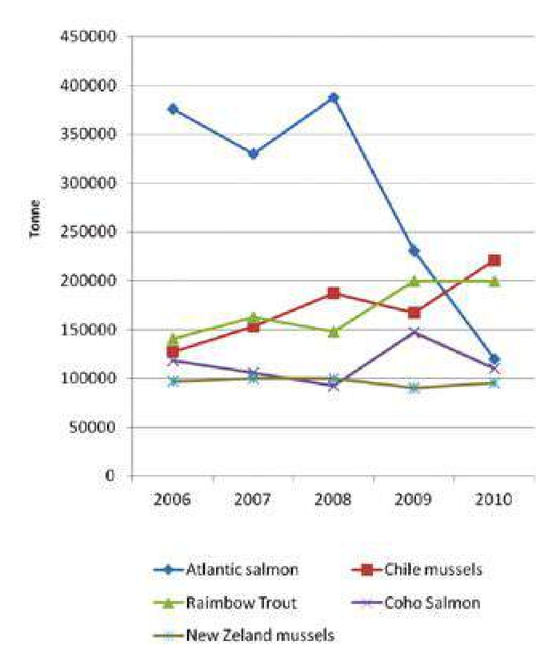
Even under the more conservative IPCC S650 scenario, which assumes that atmospheric CO_2 will only reach 563 ppm by 2100, aragonite, a form of calcium carbonate essential to shell forming in pteropods, krill and other animals that form the base of the Southern Ocean food chain, will be largely unavailable in deeper areas. For example, aragonite is only likely to be available in the first 60 meters of the water column (currently in



Source: FAO, FishStat.

Figure 3.

The top five capture fisheries species (83% of total catches, South Pacific Region and Southern Ocean).



Source: FAO, FishStat.

Figure 4.

The top five aquaculture species (87% of total production, South Pacific Region and Southern Ocean).

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[6] The International Whaling Commission and the Commission for the Conservation of Southern Bluefin Tuna have global mandates.

[7] Orr *et al.*, 2005.

the top 730 m of the Southern Ocean). The entire Weddell Sea (an important part of the Antarctic ocean) is projected to be aragonite undersaturated, giving rise to radical change in the Weddell Sea food chain with likely consequences extending to whales, penguins, albatrosses and seals.

The impact of ocean acidification in area 87 (Southeast Pacific) is to be substantial. Model results (Egger, 2011) reveal large regional variability in the Humboldt Current System's (HCS) vulnerability to ocean acidification, which is determined by long-term changes in the carbonate chemistry superimposed on natural regional variations. An initial qualitative assessment of how future ocean acidification in the HCS could affect marine organisms and ecosystems indicates that 'the natural envelope of seasonal variability in aragonite saturation levels is probably larger than the variation between present day and 2050 in the upwelling areas.' However, a bias in the model used possibly underestimated the evolution of ocean acidification in the HCS and its impact on marine organisms and ecosystems. Essentially, it is likely that there will be a progressive reduction in the healthy ocean space available for production of shellfish and other calcifiers (animals that require calcium to form their shells, or skeletons). Figures 5 and 6 illustrate these trends. In addition, the integrity of the fragile and unique Galapagoes marine ecosystem is likely to be threatened from a combination of ocean acidification, fishing and other stresses associated with population increase, tourism and economic development.

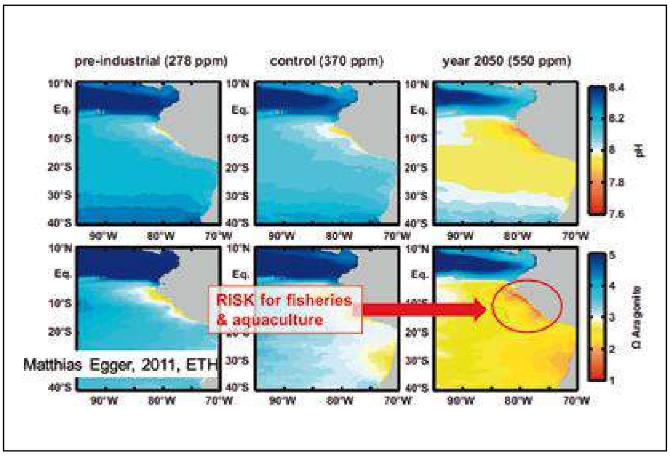

Figure 5.

A dramatic decrease in pH and aragonite saturation is projected in the Humboldt Current system (Source: Egger 2011)

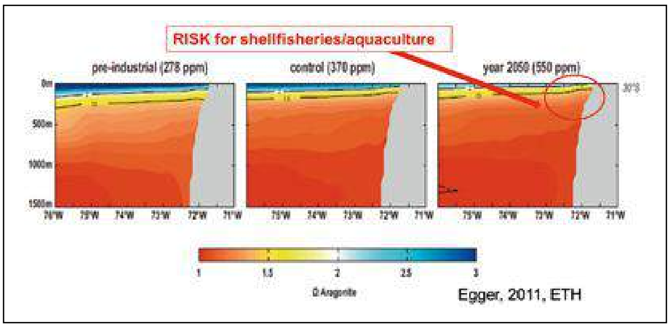

Figure 6.

Major reduction in healthy living space by 2050.

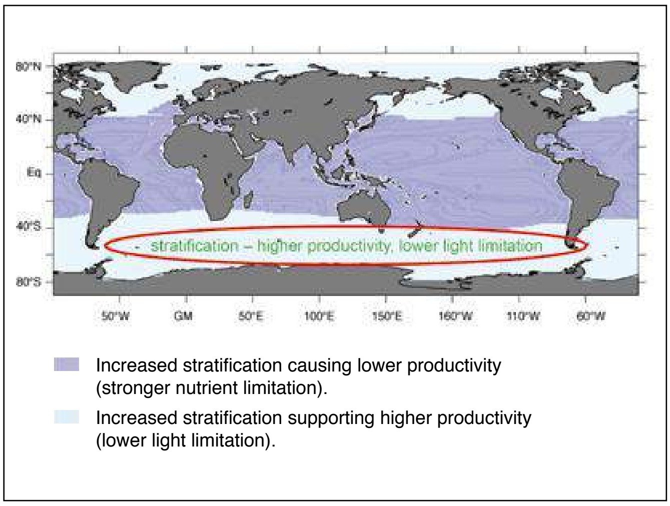

Figure 7.

Stratification resulting from ocean warming may increase productivity in the Southern Ocean.

As the geographical range of Area 81 stretches from the Southern Ocean to the sub-tropical seas of Australia, the effects vary widely. The fringes of the area are likely to be influenced by the effects described with respect to the Southern Ocean and the Humboldt Current System. The mix of fisheries ranges from the oceanic jack mackerel and Pacific blue whiting to deepwater Orange roughy and to squid, hoki and lobster. The effects on the pelagic and deepwater resources are not known. The effects on shellfish are likely to include lower growth rates, lower larval survival, lower shell weight, possibly leading to higher levels of predation and greater vulnerability to disease. Where additional stresses exist, these effects are likely to be amplified and the negative impacts on shellfish fisheries increased. These cultured species include green mussels, Pacific oyster and Sydney Rock oyster, scallops and salmon. The capture fisheries species include the pelagic species, the deepwater finfish species, deepwater crab, Wellington squid, hoki and tuna.

1.3.2. Changes in ocean temperature and salinity

In addition to significant acidification, the Southern Ocean is also generally warming[8]. This will cause greater stratification of the water column – a more well-defined differential between warmer upper layers and colder deeper waters, which in turn will limit nutrient transfers from the richer deeper waters to the more productive surface layers. On the other hand a warmer Southern Ocean is expected to have higher productivity due to reduced light limitation (Figure 7), but this increase may be modulated by micro- and macro-nutrient availability. The net outcome of the changes in these driving forces is unclear, in particular the conversion of any increased productivity into commercial fish biomass.

Moreover, in Southern Ocean and Antarctic waters the warming is occurring throughout the entire water column, that is, it is not limited to surface waters and it is occurring at a high rate

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[8] Cai *et al.*, 2010; Purkey & Johnson, 2010.

in comparison to other ocean areas. It is not only the Southern Ocean that is threatened by increased ocean temperatures as four of the world's ocean warming hotspots are in the South Pacific Region (see Figure 8). The salinity of Antarctic waters may also change as a result of ice melting. Salinity gradients are closely related to temperature and stratification and the combined effects of ocean acidification, ocean warming and salinity changes are unknown.

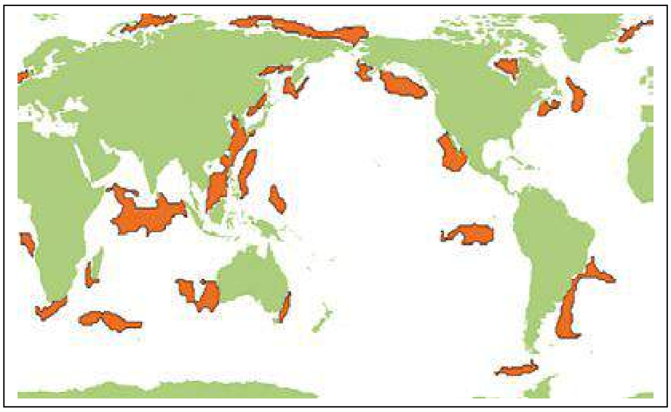

Figure 8.
Ocean warming hotspots
(adapted from Hobday and Pecl, 2014)

There is substantial evidence that ocean warming will allow warmer water species to extend their range polewards (Last *et al.,* 2010; Johnson *et al.,* 2011; Burrow *et al.,* 2014). Ocean warming will allow disease organisms and invasive species to extend their range, while the warmer oceans can disrupt life cycles, predator prey relationships and potentially result in ecosystem regime shifts. In addition to ocean acidification, increasing temperatures and expansion of low oxygen zones, many farmed species in the Southwest Pacific and Southeast Pacific face stressors such as salinity fluctuations and disease, particularly in estuarine locations, possibly resulting from sea-level rise and/or increased, or erratic rainfall causing large freshwater intrusions or flooding of estuarine areas.

1.3.3. Fishing and other stressors

Overfishing is a major stressor, largely attributable to weak governance of fisheries, involving poorly designed management regimes or failure to effectively apply management measures[9]. Illicit fishing activities are further expression of poor governance. Weak aquaculture governance is also likely to lead to stresses, for example, pollution of downstream fish farms, escapement and interbreeding of escaped fish with wild stock leading to a loss of genetic diversity which may have survival value in increasingly acidic seas.

Pollution is clearly a major stressor and the vast proportion of marine pollution originates from land-based sources[10]. In Peru and Chile mining effluent is a significant pollutant and local pollution from fish meal processing plants and from urban wastes exists. Area 87 is well south of 'the garbage patch', but marine garbage and micropollutants are growing ubiquitous problems. Altered rainfall patterns can have an additional, and sometimes quite serious, polluting effect by washing agricultural fertilizer into rivers. Wind has a significant influence on surface waters and upwelling systems and changing wind patterns may amplify the other stressors such as rainfall or wave action. Areas of low primary production such as off the coast of Columbia and Ecuador and increased UV exposure in the Southern Ocean may also act as stressors for marine species in these areas.

1.4. Biological and chemical characteristics

1.4.1. Southern Ocean

The sea surface temperature of the Southern Ocean ranges from about -1.8°C near the Antarctic coast to about 3.5°C at the polar front. Despite the cold water, the Southern Ocean is one of the more productive parts of the world ocean. Although chemical reactions and metabolic rates are slower where it is colder, the major limiting factor for marine productivity is not temperature but nutrient availability. Nutrient availability is linked to upwelling and in the Southern Ocean upwelling is connected to the seasonal formation and melting of sea ice.

As sea ice forms some salt is expelled into the surrounding water. This increases the salinity causing the sea water to become denser than surrounding water, a process aided by the cooling of surface water to subzero temperatures. The colder more saline higher density water sinks and is replaced at the surface by deeper waters that are warmer and less dense. Some of the excess salt, produced during sea ice formation, is also held in pores or spaces inside the sea ice. The process continues in the spring and summer when meltwater ponds on the surface of the sea ice, draining through the ice and washing out the salts. This process causes the exchange between surface and deepwater that keeps the surface of the Southern Ocean supplied with nutrients and is also linked to the formation of Antarctic Bottom Water – the deepwater current which is part of the 'global ocean conveyor' system that helps transfer heat from tropical to higher latitudes (Figure 9).

There is considerable variation in productivity throughout the Southern Ocean and throughout the year. On average roughly 50 tonnes of carbon is fixed per 100 km^2 of sea by phytoplankton. The location of productivity shifts during the year depending on the distribution of sea ice. As sea ice retreats in summer, centres of productivity move closer to the Antarctic continent. Nutrients tend not to be completely depleted in the surface zone during the period of phytoplankton growth, due primarily to limitation of the micro-nutrient iron. If iron were more abundant in the Southern Ocean, then phytoplankton production would be even higher. Because of the relatively high ratio of macro-nutrients to phytoplankton abundance, the Southern Ocean is referred to as a 'high nutrient – low chlorophyll environment' - the world's largest high nutrient – low chlorophyll environment area.

In a warmer Southern Ocean, primary productivity will increase, but it is uncertain if the productivity will be captured at

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[9] Pitcher *et al.,* 2009.

[10] http://www.gpa.unep.org/

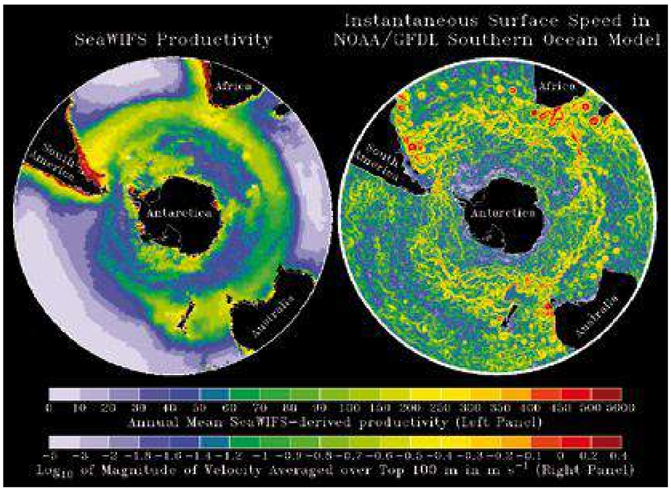

Figure 9.

Plankton blooms in the Southern Ocean may also be linked to eddy activity.

(Source SeaWiFS. http://www.gfdl.noaa.gov/visualizations-oceans)

upper levels in the food chain, i.e., converted into commercial fish biomass. The overall impacts on fisheries are largely unknown. The future vulnerability is likely to be substantially different for the key species – for the planktonic krill, for the benthic toothfish and for a range of animals in higher trophic levels: marine mammals, penguins, albatross and other seabirds. The phytoplankton blooms are the base of the food chain, but the primary productivity is transferred to the upper trophic levels by krill and pteropods which have a unique vulnerability to ocean acidification.

1.4.2. Southeast Pacific (Area 87)

Area 87 is dominated by the Humboldt Current System (HCS), the world's largest Eastern Boundary Upwelling with multiple upwelling cells along the coasts of Peru and Chile (Figure10). The system is characterized by upwelling of high CO_2, low pH, low O_2 relatively cold waters, so nutrient upwelling drives productivity but with associated risks of oxygen depletion and 'dead' zones. The El Niño is the dominant influence in the Humboldt Current system.

Primary productivity varies between 150-300 $gCm^{-2}yr^{-1}$ driven by the upwelling system (Figure11) and interrupted by El Niño events. By affecting the planktonic food sources for fish, and in particular for juvenile anchovy and sardine, the El Niño causes regime shift in the species composition of the main small pelagic fisheries alternating between anchovy and sardine dominated regimes and shifts in the horse mackerel and chub mackerel populations (Figure12). The anchovy and sardine populations however do not always vary synchronously. These species changes can have negative consequences for the fishing industry and the economies of the countries that fish the system. Around 19% of the world's catches are from Peruvian and Chilean waters. The fluctuations in the biomass also affect the mega-fauna of the area, including pelicans, seals and whales.

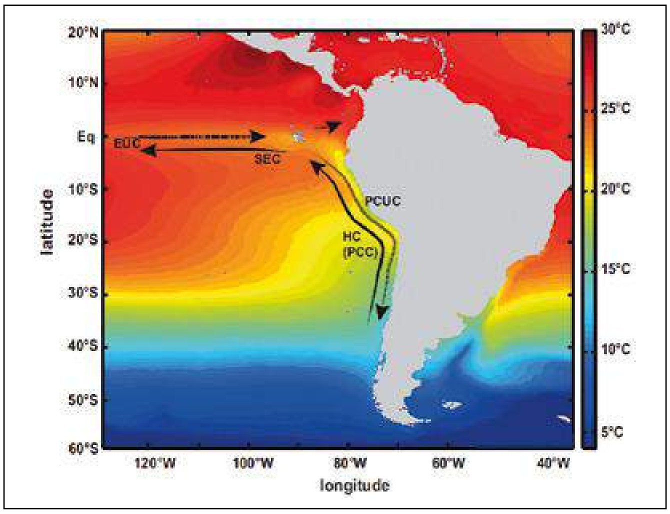

Figure 10.

Sea-surface temperature in the Humboldt Current (°C).

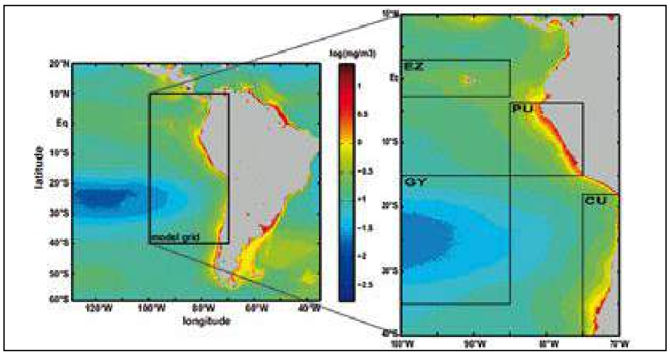

Figure 11.

Highly productive upwelling in Peru and Chile

(Chlorophyll – SeaWiFs Satellite Remote Sensing, Source Egger, 2011)

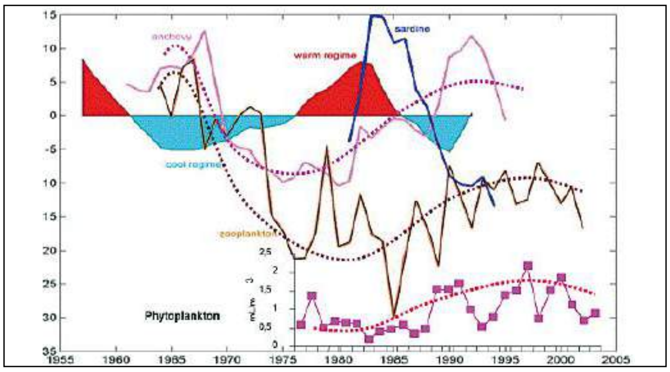

Figure 12.

Decadal' shifts in the mix of small pelagic species in the Humboldt Current system in response to El Niños.

Several areas of the HCS have intense oxygen minimum zones (OMZs), known to significantly contribute to the oceanic production of N_2O, a greenhouse gas. The contribution of the OMZs to the oceanic sources and sinks budget of greenhouse gasses (GHGs), still remains to be established[11]. However the occurrence of low oxygen conditions can have a devastating effect on aquaculture production.

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[11] Paulmier *et al.*, 2011.

1.4.3. Southwest Pacific (Area 81)

This vast oceanic area has a total surface area of 27.7 million km^2 with only 0.4 million km^2 of shelf area. It ranges from the sub-tropical waters of northern New South Wales in Australia to the northern fringes of the Southern Ocean. Several relatively weak current systems include the East Australian Current which flows south along the east coast of Australia, part of which turns east after coming in contact with the West Wind Drift along the northern edges of the Southern Ocean and southern margin of the Tasman Sea and blends with the East Cape Current to form to form the Wairarapa Gyre in the area of the Chatham Rise. Within the Region, there are two shallower plateaus of about 200–1000 m in depth. The largest is the Campbell Plateau, which occurs to the southeast of New Zealand below 46°S. The second, the Lord Howe Rise, is shallower and extends from the centre of New Zealand in a northwesterly direction. The types of habitats are very varied, supporting a wide range of fisheries, from coastal continental to deep-water seamount fisheries. The Region is mostly deep oceanic water, with many seamounts[12] (see Figure 13) where bathypelagic fish resources such as orange roughy and oreos are exploited.

1.5. General socio-economic aspects of the Region

This section focuses principally on describing[13] the fisheries of the Region, which are of global importance and of great economic significance particularly to Peru, Chile and New Zealand. Despite its diversity, the Region has several common fisheries characteristics :

- relatively low population pressure throughout the Region and relatively low fish consumption;
- a major net exporter of seafood – fishmeal, small pelagic fish, salmon, mussels;
- the vast majority of the production is industrial, or large scale fishing and aquaculture;
- a number of distant water fishing nations (DWFN), or flag states which are not among the coastal states of the Region, have a significant fishing presence;
- there are important small-scale fisheries and aquaculture operations, particularly in Latin America;
- the Region has the world's largest single species fishery (Humboldt anchoveta);
- the Region contains a fishery resource with high future potential (Antarctic krill 5.6 million ton precautionary TAC of which about 0.25 million tons is currently harvested);
- the Region offers a range of fisheries governance lessons.

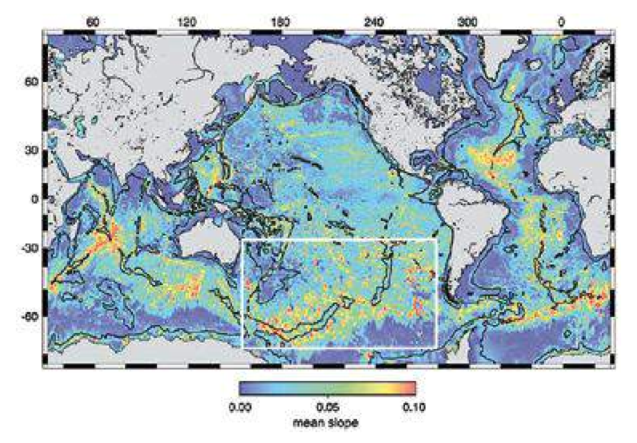

Figure 13.
The concentration of seamounts in the South Pacific Region.

The countries fishing in the Region include: Canada, China, the Cook Islands, Netherlands, Estonia, Georgia, Japan, the Republic of Korea, Latvia, Lithuania, Norway, Poland, the Russian Federation, Spain, Taiwan Province of China, Ukraine, Uruguay, Argentina, and the United States of America. As indicated in Table 2, aquaculture is of growing importance.

Table 2.
Main marine and brackish-water aquaculture production in 2011 in the Region by species group (tons).

Country/ species group	tons
Chile	245,274
algae	12,162
salmonids	608,266
molluscs	233,112
Ecuador	223,315
shrimp	223,313
New Zealand	109,967
salmonids	12,280
molluscs	97,687
Peru	58,103
molluscs	58,101

Source: FAO, FishStatJ.

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[12] Wessel *et al.* 2010.

[13] Information in this section drawn mainly from: FAO. 2011.

1.5.1. Southern Ocean (Areas 48, 58, 88)

The Southern Ocean represents about 15% of the world's ocean area. A number of countries, including Australia, France, UK and South Africa have island territories in the Southern Ocean. The Antarctic Convergence (50°S - 60°S) formed by cold, northward-flowing Antarctic waters separates two hydrological regions with distinctive marine life and krill as a keystone species. Catches from the Southern Ocean are dominated by those from the Antarctic Atlantic with 90% of the total recorded catches from the Southern Ocean in 2009. The overall catch of the Antarctic Atlantic (Area 48) has shown a steadily increasing trend to 131,700 tonnes in 2009.

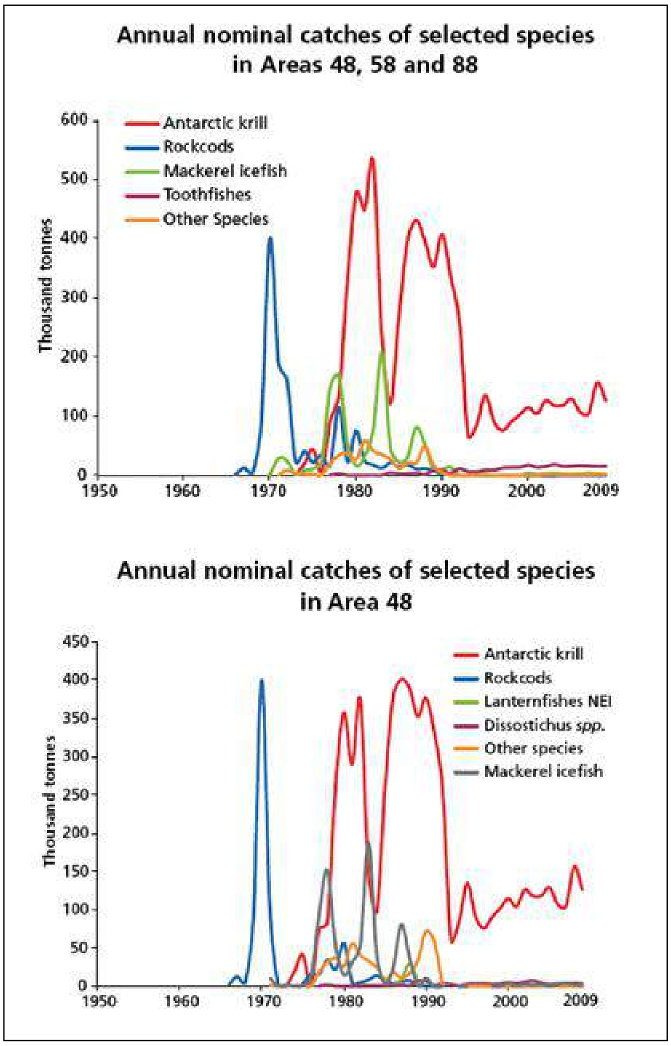

Figure 14.
Trends in catches in the Southern Ocean illustrating the dominance of Area 48.

In the 1980s and 1990s (see Figure 14), fishing focused on krill, mackerel, icefish and, to a limited extent, squid and crab. The development of new harvesting technology and markets in recent years has seen growing interest in fisheries targeting Antarctic toothfish (*Dissostichus mawsoni*) Patagonian toothfish (*Dissostichus eleginoides*) adjacent to the Antarctic continent, and renewed interest in krill fishing. In the 1990s and early 2000s, unreported catches of toothfish and related high-value demersals may have exceeded the reported catch by five to six times. At its peak in 1982, the krill fishery contributed about 13% of the global annual catches of crustaceans. Commercial whaling ceased in 1987 and there has been no commercial sealing since the 1950s.

1.5.2. Southeast Pacific (Area 87)

Ecuador's aquaculture is particularly important with a production of about 300,000 tons worth $1.4 billion (2011) comprising mainly shrimp and tilapia. Ecuador also has an important tuna fleet and tuna processing industry and the Galapagos biodiversity hotspot is also in Ecuador waters. There are about 250,000 fisheries jobs – approximately 4% of the workforce and Ecuador has the largest artisanal fishing fleet in all the Southeast Pacific countries. The large industrial tuna purse seine vessels can fish in more distant waters of the Central Pacific. Total fisheries production is in the order of 400,000 tons per year.

Table 3.
Recorded capture fisheries production ('000 tons)

	2005	2006	2007	2008	2009	2010	2011
Peru	9,350	6,983	7,177	7,360	6,873	4,220	8,216
Chile	4,698	4,421	4,087	3,897	3,782	3,015	3,431
Ecuador	430	415	362	447	449	340	452
Columbia	-	-	80	70	45	52	52
Venezuela	19	34	27	37	27	12	31
Total	14,497	11,854	11,733	11,811	11,175	7,638	12,181

Source: FAO, FishstatJ.

Between 150,000 and 170,000 people depend directly on Peru's fisheries for employment and income. The large-scale industrial fishery dedicated to export production provides about 30,000 jobs and the artisanal fishery employs about 65,500 engaged directly in fishing operations and a further 19,200 employed by fishery-based food processing for direct human consumption. The artisanal fisheries use about 10,000 vessels and contribute greatly to the country's food security by producing between 200,000 and 400,000 tons per year. The challenges facing Peru's fisheries include: maintaining sustainable levels of exploitation in the face of El Niño-driven fish stock variability; pollution, mainly associated with a lack of or inadequate treatment of sewage, waste waters and solid waste generated by coastal cities, poorly controlled mining operations and pollution from activities such as oil and gas production, transport and storage, fish processing and aquaculture, agriculture and several other manufacturing activities.

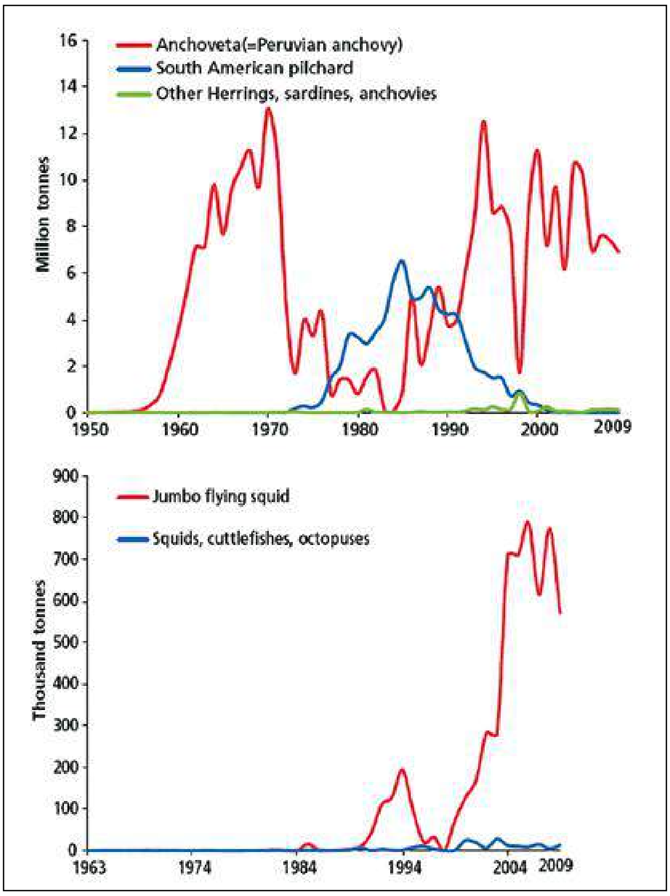

Figure 15.
Variability in the anchovy fishery and the rise of the cephalopod fisheries.

Chile's fisheries are dominated by the industrial fisheries, but are also the basis for the livelihoods of about 85,000 artisanal fishers. Declining catches in key resources have generated conflicts between the sub-sectors. Almost all the fisheries are considered[14] either fully, or over-exploited and three out of the 33 main fisheries are considered collapsed. Until 2007 Chile experienced rapid growth in its salmon aquaculture becoming the second largest salmon and trout producer after Norway, contributing 38% of the world's salmon supply. Salmon was the third largest export product in terms of value (3.9% of Chile's exports). A severe outbreak of infectious salmon anaemia in 2007 caused salmon production to fall from 400,000 to 100,000 tons in 2010. Chile also grow turbot, mussels, scallops, oysters and algae. Key species for aquaculture include Atlantic salmon and Rainbow trout, Whiteleg shrimp, Coho salmon, Chilean mussels, Gracilaria seaweed and Peruvian calico scallops.

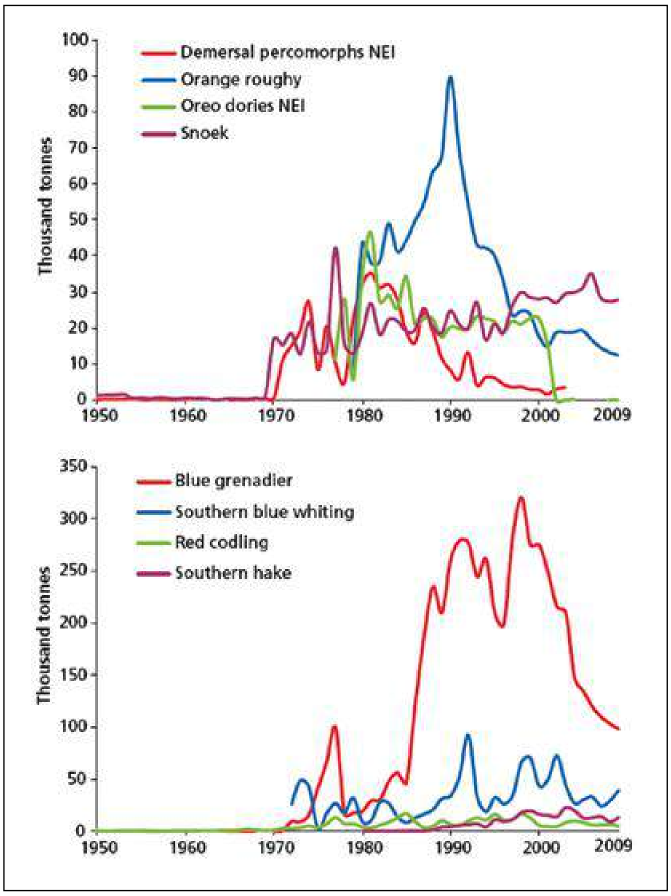

Figure 16.
Trends in the catches of major species in Area 81.

1.5.3. Southwest Pacific (Area 81)

Catches reached a peak of about 900,000 tonnes in the 1990s and have now stabilized at around 600,000 tonnes (2009). Five taxonomic groups account for 81% of the catches: gadids (cods, hakes, haddocks, 30%), squids, cuttlefishes and octopuses (10%), tunas, bonitos and billfishes (8%) other bottom fish (21%), other pelagic species (11%).

There are only two countries in Area 81, Australia and New Zealand. New Zealand has the largest landings, with a peak of 650,000 tonnes in 1998 and 420,000 tonnes in 2009. Japan caught the second-largest volume in Area 81 and landed 300,000 tonnes in 1988, but withdrew after 2006. Australia's landings from Area 81 increased gradually from 10,000 tonnes in 1950 to 30,000 tonnes in 1985, and then experienced a rapid growth to a peak of 80,000 tonnes in 1990. The total catch then fell sharply to about 20,000 tonnes in 2009. Recreational fisheries are important in Australia and New Zealand. The Republic of Korea also has a strong presence in Area 81, with catches of about 50,000 tonnes in 2009.

Orange roughy, snoek, oreo dories and similar species make up the 'other demersal species' (21% of catches; Figure 16). Orange roughy increased rapidly to reach a record high of more than 80,000 tonnes in 1990 with a dramatic decline to about 10,000 tonnes landed in 2009. Snoek catch has increased quite steadily to 25,000 tonnes in 2009. New Zealand and Australia have been

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[14] Subpesca, 2013.

pioneers in developing profitable and sustainable deepwater (> 600 m) trawl fisheries. These fisheries include fisheries off New South Wales. For New Zealand the targets include the pelagic resources in the Southwest Pacific and the bathypelagic species associated with the sea bottom rises from the Tasman Sea east to the south, and east of the South Island of New Zealand. The most important species caught in these fisheries are orange roughy (*Hoplostethus atlanticus*) and hoki (*Macruronus novaezelandiae*).

Wellington "flying squid" and various other squids make the third-largest contribution to catches in Area 81. The landings of Wellington flying squid have varied greatly between 20,000 tonnes and 100,000 tonnes, and were about 50,000 tonnes in 2009. The catch of other squids have fluctuated widely and declined overall from a peak of 70,000 tonnes in 1980 to 20,000 tonnes in 2009. Horse mackerel is the most important pelagic species with an average catch of 100,000 tonnes in the 1990s.

Sydney rock oyster *Saccostrea glomerata* (native) and Pacific oyster *Crassostrea gigas* (introduced) are both important species in Australia. In addition, the Pacific oyster is also farmed in parts of New Zealand. The annual value of these species to the Region's fisheries is approximately $40 million for the Sydney rock oyster and $22 million for the Pacific oyster. They also have ecological significance providing habitat structure for benthic organisms in the region, acting as a biological purifier for polluted estuarine water and a food source for other organisms (Gutiérrez *et al.,* 2003). Other key aquaculture species include: New Zealand mussel, Sydney cupped oyster, Atlantic salmon and Rainbow trout.

For Australia (New South Wales), ocean warming is a major driver of regime shifts as tropical species move south[15]. There is also evidence of temperature stresses on bivalves and *in vitro* evidence of ocean acidification stresses on cultured species. If acclimation across multiple generational does not occur, selective breeding of oysters (and potentially other molluscs) may be an avenue for aquaculture to reduce the impacts of ocean acidification on stocks. However, this will come at an additional cost to production.

2. BIOLOGICAL IMPACTS OF OCEAN ACIDIFICATION

The biological impacts of ocean acidification need to be taken into account in the fisheries management regimes and an overview of these regimes and approaches provides a useful framework for action. The fisheries management regimes can be considered at two levels: national management and regional management. At both levels the Region provides some lessons in fisheries governance. Throughout the Region, a limited number of key actors facilitate dialogue and action. This includes a limited number of industrial fisheries 'giants' in most countries and a consolidated aquaculture industry and aquafeeds industry. However, there are also large numbers of small-scale fishers in Latin America.

2.1. National fisheries management regimes

Australia and New Zealand have robust governance of fisheries and despite some setbacks their fisheries are largely sustainable[16]. Introduction of an ecosystem approach has grounded management advice in a more holistic science base. Attention to the political economy of fisheries has led to strengthened fishing rights creating incentives for rights-holders to conserve and value the resource base. In some cases this may have come at the cost of a concentration of wealth, in others (such as in New Zealand) the benefits have been spread through community ownership of fishing rights. Peru has had a major governance reform in the anchoveta fishery with economic rents increasing by up to $0.5 billion per annum. Chile is benefiting from lessons from a collapse in salmon aquaculture due partly to poor aquaculture governance, concentration of farms and failure to enforce disease controls. Chile also has strong small-scale cooperative movement, but conflicts between industrial and small-scale fishers are ongoing.

Australia, New Zealand, Chile and Peru all have well developed and resourced fisheries research and management institutions, produce regular 'state of the fisheries resources' analyses and are actively studying climate change adaptation options for fisheries and their marine economies. Australia has created the Heard and McDonald Islands Marine Reserve[17], a 65,000 km^2 area around the uninhabited Heard and McDonald Islands and includes two large zones of the Southern Ocean. The reserve is intended to protect the habitat and food sources of seals, penguins, albatrosses and ensure that this pristine ecosystem remains intact. Ecuador manages the 133,000 km^2 Galapagos Marine Reserve.

2.2. International management

The international fisheries bodies include CCAMLR, IWC, SPRFMO and CCPS. Three RFMOs, WCPFMC, IATTC and CCSBT are charged with tuna management and their role is addressed in other chapters where the tuna fisheries are of more importance.

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[15] Figueira and Booth, 2010.

[16] http://fish.gov.au/Pages/SAFS_Report.aspx

[17] www.environment.gov.au/coasts/mpa/heard/

Commission for the Conservation of Antarctic Marine Living Resources

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)[18] was established by international convention in 1982 with the objective of conserving Antarctic marine life in the 32 million km^2 area of jurisdiction (see map Figure 1), including seabirds and the management of fisheries in the Southern Ocean. CCAMLR is an international commission with 25 Members, and a further 11 countries have acceded to the Convention. With responsibility for the conservation of Antarctic marine ecosystems, CCAMLR practices an ecosystem-based management approach and has adopted principles that aim: to balance harvesting and conservation; to protect the needs of dependent species, and to avoid irreversible ecosystem changes. CCAMLR has pioneered ecosystem approaches to fishery and environmental management, through the incorporation of precaution and uncertainty into its management procedures and by establishing an ecosystem monitoring programme using indicator species and processes. This approach permits harvesting, as long as such harvesting is carried out in a sustainable manner and takes account of the effects of fishing on other components of the ecosystem. Based on the best available scientific information, the Commission agrees a set of conservation measures that determine the use of marine living resources in the Antarctic. It has met with some success, notably in applying conservative yield models for toothfish and krill stocks and in establishing strict rules for undertaking new and exploratory fisheries.

The International Whaling Commission has responsibility for the conservation of whales. A related convention, The Convention for the Conservation of Antarctic Seals, ratified in 1978, reports to the Scientific Committee on Antarctic Research, which undertakes the tasks requested of it in the convention.

South Pacific Regional Fisheries Management Organization (SPRFMO)

The South Pacific Regional Fisheries Management Organization (SPRFMO) was established in response to growing concern over the over-exploitation of seamounts and the jack mackerel and 'jumbo' squid fisheries in the high seas off the coast of Chile and Peru. The objective is the conservation and sustainable use of fishery resources and to safeguard the marine ecosystems in this area (Figure 17). SPRFMO has set a limit of 360,000 tons for *Trachurus murphyi* in the convention area and prohibited the use of large gillnets.

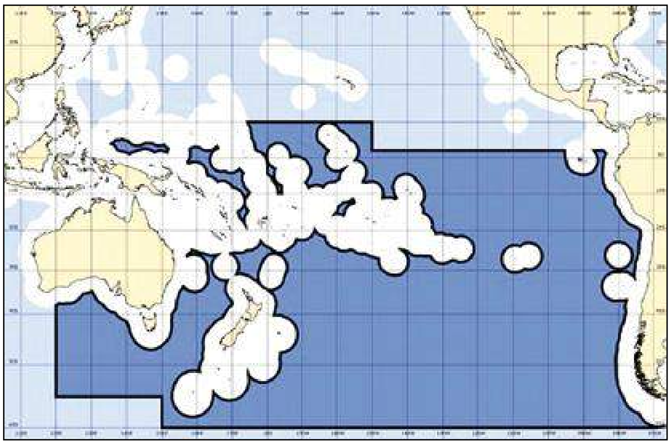

Figure 17.
SPRFMO Convention area
(note exclusion of Exclusive Economic Zones).

Permanent Commission for the South Pacific (CPPS)

The CPPS coordinates regional maritime policies in order to adopt concerted positions of its Member States (Chile, Colombia, Ecuador and Peru) in international negotiations, development of the Law of the Sea, International Environmental Law and other multilateral initiatives. CPPS is engaged in a capacity-building process at the national and regional levels in the areas of science, socio-economic policy and the environment. CPPS promote linkages between marine research and regional policies. It coordinates and fosters research activities related to the ecosystem approach, climate change, operational oceanography, natural disaster mitigation, living and non-living resources, as well as issues associated with fishing and aquaculture, including economic and social aspects and related activities. Its area of competence has no specific geographical coordinates.

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[18] www.ccamlr.org

2.3. Ocean acidification effects on the selected species

There are few studies of the effects of ocean acidification on the Region's species. Only three species have been used in laboratory studies on ocean acidification: Sydney rock oyster *Saccostrea glomerata* (Area 81), Pacific (cupped) oyster *Crassostrea gigas* (Areas 81, 87) and Jumbo flying squid *Dosidicus gigas* (Area 87). Of these species two were from populations within FAO Area 81. No studies on populations from Areas 87, 88, 58 or 48 were identified.

Finfish

The sensitivity of finfish to ocean acidification is largely unknown but recruitment success may be impacted, there may be a reduction in metabolic rate, growth, in reproduction and survival, or impacts on larval development and hatching success. There may also be indirect impacts on finfish, through the vulnerability of key food species, such as pteropods and krill to ocean acidification, or through destruction of key habitats (such as ice, cold water corals, or shellfish beds). There are likely to be increased energetic requirements. The cumulative impact of ocean acidification and other stressors, such as ocean warming is not well understood. The effects on key mariculture species (Rainbow Trout, Atlantic Salmon) is not known, but impacts on anchovy and krill fisheries could affect supply of key feed ingredients such as fish oil and amino acids.

Crustacea

Preliminary results of one study on krill indicated that elevated seawater pCO_2 is likely to increase mortality, reduce activity levels and fitness, and cause moult cycle irregularities on post-larval krill. No significant effects on growth rates and intermoult period were observed under experimental conditions in this study. A workshop in 2011 concluded that the cumulative impact of climate change on krill is probably negative (IMARES, 2011). The evaluation focused on major agents of climate change, such as ocean warming, sea ice loss, and ocean acidification. Exposure of Antarctic krill to elevated CO_2 of 1000 ppm and 2000 ppm (pH 7.7 and 7.4, respectively) for 26 days, led to a significant decrease in hatching success of the crustacean species (Kurihara *et al.,* 2008).

Shelled molluscs

A number of laboratory studies have shown that a species response to ocean acidification can vary significantly across different populations (Berge *et al.,* 2006; Gazeau *et al.,* 2007; Kurihara *et al.,* 2007; Havenhand and Schlegel, 2009; Parker *et al.,* 2010; Thomsen and Melzner, 2010). It is therefore important to assess the impacts of ocean acidification on specific populations within the different FAO Areas before any realistic predictions of socio-economic impacts on the regions can be made.

Studies on the early-life history stages of Australian populations of oysters have shown that they are extremely vulnerable to elevated CO_2 (Parker *et al.,* 2009; Watson *et al.,* 2009; Parker *et al.,* 2010; Parker *et al.,* 2012). At elevated CO_2 there is a reduction in the fertilisation success of gametes, a reduction in the development of embryos and size of larvae and spat and an increase in abnormal morphology and development time of larvae for both species. These effects are greater for the native *S. glomerata* than the introduced *C. gigas*. Combined, elevations in pCO_2 of 750–1000 ppm and temperature (+4 ˚C) resulted in 100% mortality of D-veliger larvae of *S. glomerata*. In contrast, the same pCO_2 and temperature combination resulted in only 26% mortality of D-veliger larvae of *C. gigas.* In adults of the Sydney rock oyster, exposure to elevated CO_2 caused a significant increase in standard metabolic rate (SMR), suggesting a higher energetic cost of routine metabolism as our oceans continue to acidify (Parker *et al.,* 2012). In Pacific oyster populations outside of FAO Area 81, ocean acidification caused a significant reduction in shell calcification (Gazeau *et al.,* 2007) and an increase in SMR (when ocean acidification was combined with elevated temperature; Thomsen and Melzner, 2010). Further, in the Pacific Northwest coast of the United States, there have already been year-by-year declines in the survival of juvenile 'seeds' of the Pacific oyster due to the upwelling of acidified water (Barton *et al.* 2012).

Smaller larvae with thinner, weaker shells may require a longer length of time in the plankton to have sufficient energy for metamorphosis. A longer larval life may also decrease survival due to the increased risk of predation and exposure to other environmental stressors. In addition, reduced calcification in adults may lead to reduced protection from predators, parasites and unfavourable environmental conditions (Beniash *et al.,* 2010).

While studies on the native Sydney rock oyster have suggested that it is extremely vulnerable to ocean acidification, particularly during the early-life history stages, there is evidence that some populations of this species may have the potential to acclimate or adapt. For example, Sydney rock oyster populations that have been selectively bred by industry to grow faster and have resistance to disease are more resilient to elevated CO_2 than the wild population, with newly metamorphosed spat from selectively bred populations experiencing only a 25% reduction in shell growth after 4 days at elevated CO_2 compared to the 64% reduction in shell growth experienced by the wild population (Parker *et al.,* 2011). In addition, a recent longer term study has found that positive carryover effects may be passed from adults to their offspring during exposure to elevated CO_2. Larvae produced from parents reared at elevated CO_2 were larger in size and developed at a faster rate under elevated CO_2 when compared to larvae produced from parents conditioned under ambient CO_2 conditions (Parker *et al.,* 2012)

Similar studies could be envisaged for other commercially important molluscs such as, abalone, New Zealand mussel, Peruvian scallop, loco and other species. In addition, possible increased vulnerability of shellfish populations to disease (such as the protozoan QX disease or Ostreid herpes) as a result of ocean acidification could be explored.

Cephalopods

The jumbo flying squid *Dosidicus gigas* is widely distributed in the Southeast Pacific and supports an important fishery (Liu, 2010). Peru and Chile have the largest landings of *D. gigas* in the Pacific Ocean with landings over 0.5 million tons in 2011 in Area 87. *D. gigas* is a large pelagic top predator which already occupies habitats at the upper and lower extremes of its temperature and oxygen threshold limits. A study assessed the impacts of ocean acidification (in combination with elevated temperature) on *D. gigas* populations outside of FAO Area 87 (Rosa and Seibel, 2008). During acute exposure to elevated CO_2, *D. gigas* experienced a significant reduction in SMR (31%) and activity levels (45%). When temperature was elevated past the threshold limit of the squid, the effects of ocean acidification on SMR and activity levels were exacerbated. This suggests that in a high-CO_2, high-temperature ocean, this reduction in SMR and activity levels will impair predator-prey interactions and have consequences for growth, reproduction and survival and distribution of the species (Rosa and Seibel, 2008). Further, expansion of the OMZ in the region will mean that, in the absence of acclimation, *D. gigas* will have to horizontally migrate to shallower, less hospital waters at night to feed and repay any oxygen debt which has accumulated during their diel vertical migration to the OMZ (Rosa and Seibel, 2008).

Other organisms

Ocean acidification is also a threat to cold water corals and the management of vulnerable marine ecosystems (VMEs). Ocean acidification may have additional indirect effects by promotion of biofouling organisms or spread of undesirable invasive species.

In summary, there is limited empirical information on the effects of ocean acidification on commercial species in the South Pacific Region and negligible information on the impacts at the population and ecosystem level.

Table 4.
Balance of fish trade and domestic fish supply 2007.

	Fish imports (tons) 2007	Fish exports (tons) 2007	Domestic supply (tons)
Australia	572,821	157,285	743,594
New Zealand	45,974	585,466	112,782
Colombia	230,538	107,966	305,216
Ecuador	79,500	542,062	174,778
Peru	58,873	10,562,956	1,138,704
Chile	240,028	3,356,023	1,491,640

3. ECONOMIC IMPACTS OF OCEAN ACIDIFICATION

It is difficult to estimate the economic impact of ocean acidification for several reasons :

- the direct impact on many commercial species is unknown, let alone the indirect effects via impacts on other important linked ecosystem components.
- the capability of species and ecosystems to adapt is not well understood.
- other commercial species may substitute stressed species.
- the impact of other stressors varies widely and the combined impacts are not well understood.

Table 5.
Economic, nutritional and environmental indicators.

	Fish as % protein supply	Fisheries employment (%)	Fisheries % GDP	EPI Trend
Australia	8.29%	0.72	0.13%	No change
New Zealand	13.78%	0.5	0.79%	No change
Colombia	4.94%	3.1	0.12%	Modest improver
Ecuador	5.40%	13.24	2.72%	No change
Peru	23.39%	2.59	2.06%	Declining performers
Chile	20.17%	3.3	2.51%	Declining performers

Table 6.
Exports of the Region by commodity and country (2011)

Commodity	Value ($)	Country	Value ($)
Fish meal/ oil	2,493,143	Australia	829,684
Finfish	2,182,787	Chile	3,692,739
Crustacea	1,354,614	Colombia	209,084
Salmonids	1,142,060	Ecuador	1,612,094
Molluscs (excl. cephalopods)	998,737	New Zealand	906,019
Tuna	635,294	Peru	2,218,406
Small pelagics	263,942	Total	9,477,932
Cephalopods	162,071		
Miscellaneous	152,645		
Seaweeds	33,210		
Sharks	19,356		
Other invertebrates	4,301		
Total	9,442,160		

Source: FishStatJ. Note that values include total Australian exports (i.e. not only Area 81) and also all Columbia exports.

If the export commodities are assumed to be a representative mix of products, then 25% of the Region's fish products by value are crustacea and (shelled) molluscs, which are also the most vulnerable to ocean acidification. However, given that the balance of the commodities is largely finfish, most of which depends on crustacea at different stages of their life cycle, the entire fishery economy may be subject to negative economic impacts. The following tables provide an order of magnitude of the Region's fishery economy.

It is not only the coastal states of the Region which may be impacted. The trading partners and product users, particularly the aquaculture industry (a major fishmeal/ oil user) could be impacted by higher prices. Approximately 17 Distant Water Fishing Nations that catch over 0.75 million tons in the Region could also be impacted (Table 9).

Table 7.
Value of aquaculture production 2009

Country	Value US $
Chile	6,004,147
Ecuador	1,287,000
Peru	474,025
Australia*	461,489
New Zealand	274,297
Total	8,500,958

Source: FishStatJ.
*Note that values include total Australian production (i.e. not only Area 81)

Table 8.
New South Wales reported commercial wild harvest for 2006/2007

Species/ fishery	Reported Gross Tons	Estimated Value Aus$'000
Abalone	121.8	4,980
Estuary General	3,657	20,831
Estuary Prawn Trawl	522	3,905
Lobster	109.4	5,200
Ocean Hauling	6,045	16,152
Ocean Trap and Line	1,854	10,556
Ocean Trawl	3,476	21,501
Sea Urchin and Turban Shell	55	86
Inland	25	46
Total	**15,865**	**93,813**

Table 9.
Recorded catches by costal states
and Distant Water Fishing Nations in the Region (2011) (tons)

Coastal states (9)	2011 catch	DWFN (17)	2011 catch
Peru	8,217,517	China	302,635
Chile	3,466,611	Norway	102,460
Ecuador	451,589	Korea, Republic of	97,160
New Zealand	420,039	Ukraine	65,018
Colombia	51,586	Japan	55,169
Australia	23,206	Taiwan Province of China	40,195
France	7,434	Panama	38,288
United Kingdom	1,597	Venezuela	30,608
South Africa	162	Spain	25,212
		Vanuatu	7,771
		Nicaragua	6,070
		Poland	3,713
		Netherlands	1,145
		Portugal	638
		Germany	471
		Russian Federation	467
		Uruguay	39
	12,639,741		777,059

Source: FishstatJ

4. FORECASTS AND SCENARIOS

The most critical scenarios identified are: (i) the major reduction in healthy living space for marine species by 2050 in the Humboldt Current upwelling system due to aragonite undersaturation and the shrinking aragonite window; and (ii) the projected aragonite undersaturation in the Southern Ocean. Both have been described above and are likely to lead to major changes in these ecosystems. These scenarios strongly suggest that the South Pacific will be the earliest area in this Region to experience large-scale ocean acidification impacts.

Current information suggests that for existing ecosystems and the majority of commercial species in the South Pacific Region, the outlook is negative. However, for some species including seaweeds and cephalopods the perspective appears plausibly more favourable, although it is important to acknowledge significant knowledge gaps even for these groups. It could also be speculated that for species with an r-selection strategy (short life cycle, high fecundity), a changing environment may favour their adaptation to a more acidic ocean.

The combination of stressors, including acidification and warming oceans, and fishing pressure and the responses of species through adaptation or changing distribution and life cycles, makes forecasts of ecosystem changes tenuous and at this stage the socio-economic impacts cannot readily be assessed.

5. POLICY RECOMMENDATIONS

5.1. Mainstreaming knowledge and actions

The generic mainstreaming process requires raising awareness at all levels with a focus on policy makers, scientific priorities and international processes. Strategic pathways should be identified with clearly articulated goals in order to build political support for priority actions. It means harnessing a realistic ocean acidification agenda to global processes and fora (e.g. UNGA, G8, OECD, SIDs,). In the South Pacific Region the entry points would include the regional fisheries bodies and the Antarctic treaties and conventions processes, the fishing, fishmeal and aquaculture production and feeds industry organizations and the major conservation NGOs.

The mainstreaming process requires that ocean acidification is an active item on the relevant agendas, and that appropriate information packages are made available and a coherent ‘story line’ is prepared in terms of actions requested from the various fora. In general it may be useful to target key fisheries (the largest, most valuable, or where there is the highest level of social dependence). The ocean acidification issue needs to be integrated within actions for conservation, sustainable use, poverty reduction, climate change adaptation and mitigation agendas. Public understanding of ocean acidification is generally poor and the ocean acidification messaging may need to be tailored to the interests of different stakeholders and recognition that they are stakeholders. A relatively coarse segmentation of stakeholders can identify, for example: industrial players - aqua feeds, krill producers, small pelagic companies (among the largest fishing companies in the world); indigenous people and cooperatives in Chile, New Zealand and elsewhere; the aquaculture insurance industry.

5.2. Building consensus science

A major challenge will be to build scientific consensus on key ‘unknowns’ — trends, orders of magnitude, geographies, underlying assumptions and quantifying uncertainties. While progress has been made on integration of ocean acidification into the UNFCCC processes, further institutional mechanisms may be required to rapidly filter and synthesise the science. It may be necessary to prioritise the scientific questions, for example with a focus on (i) keystone calcifiers; (ii) on the main commercial species; (iii) on the cumulative impacts ocean acidification and other stressors; (iv) on the adaptation capacity in species such as corals; and (v) on the possibility of local mitigation through seaweed culture or other means. Ecosystem level impacts may require a long-term research framework to be identified as it will be a challenging long-term research area.

5.3. Identifying actions

It will be important to identify priority mitigation and adaptation actions, their costs, and costs of inaction, and who pays the costs. Many of these actions will involve the application of known best practices of sustainable development, such as responsible fisheries and application of the Code of Conduct for Responsible Fisheries, use of integrated coastal management (ICM), or pollution reduction initiatives. Ideally these actions would be accompanied by financing for a sound business case, with a possible expansion of blue carbon markets.

The level of and trends in ocean acidification in many major fishing areas is unknown, so efforts to monitor ocean acidification levels in key fisheries areas and to include vulnerability to ocean acidification in mapping multiple marine stresses (acidification, warming, deoxygenation, pollution, fishing) will be important, as the key mitigation actions are likely to be directed at reducing the other stressors. A minimum level of information on impacts will be required to include ocean acidification risk in fisheries advice and models. Selective breeding for ocean acidification resilience could be a useful approach for commercial aquaculture species.

In order to finance an action agenda it will be useful to prepare a strategic plan with associated costs, allocation of responsibilities and an institutional framework in order to invite funding and coordinate activities at various levels. The South Pacific Region may offer some opportunities for several reasons: the early advent of the ocean acidification impacts; the quality of marine science in the area; the presence of pristine marine parks; comparatively well-managed fisheries; potential for a strong business case and integration with existing pollution control and climate change agendas; and a limited number of major players in fisheries and aquaculture.

6. SUGGESTIONS FOR FURTHER RESEARCH NEEDED TO FILL THE GAP BETWEEN NATURAL SCIENCES AND ECONOMICS

At the **process** level several questions may be considered:

- what is the consensus scientific knowledge required to complete basic estimates of economic impacts, estimates of losses, risks to economies?
- what would a focused major awareness effort need?
- what are the costs of defined priority actions – national and/or global?
- who can support the costs of priority actions/ how will this be financed?
- what is the shape of an ocean acidification agenda – is it best to split or lump/ work with or in parallel to main climate change processes or other agendas. What are the advantages, disadvantages, alternatives?
- who can take responsibility for coordination of ocean acidification agenda and under what mandate?

At the **policy** and strategic levels advice may be usefully developed on the following questions:

- how to build the business case for action on ocean acidification.
- how to link ocean acidification to the poverty and growth agendas.
- how to target major concerns, such as jobs, food security, natural disasters.
- how to engage private sector and civil society.
- how to prioritize an ocean acidification action agenda.

Building on approaches to **adaptation** to climate change the following questions are applicable to ocean acidification adaptation:

- how to increase the resilience of most vulnerable people.
- identifying the synergies between adaptation and mitigation.
- specifying ‘no-regrets’ or ‘low-regrets’ actions and reversible and flexible options.
- identifying safety margins for more informed investments later.
- how to link to other agendas – green accounts, payment for ecosystem services.

A number of specific or **technical** research questions arise from the examination of the South Pacific Region:

- Studies are needed on the variability of the depth of the upper limit and thickness of the Oxygen Minimum Zone (OMZ), the depth of low pH and high CO_2 waters and depth of the aragonite saturation horizon in the Humboldt Current upwelling system, all likely to be key compounding factors in ocean acidification impacts.

- CCAMLR will need to develop research programs to fill in the gaps of current research on Southern Ocean impacts as soon as possible. Longer-term studies of acidification for the entire lifecycle of important species are needed, including implications for non-calcifying organisms and impacts of ocean acidification on other biological processes besides calcification in invertebrates and vertebrates. In particular critical knowledge gaps in the biology and ecology of Antarctic krill need to be closed, including on recruitment processes, under-ice and benthic habitat use, their capacity to adapt to environmental change, their ecosystem function, as well as the energy demand and food consumption of krill-dependent predators.
- If acclimation does not occur, selective breeding of oysters (and potentially other molluscs and corals) may be an avenue for aquaculture to reduce the impacts of ocean acidification on stocks. However, this will come at an additional cost to production.

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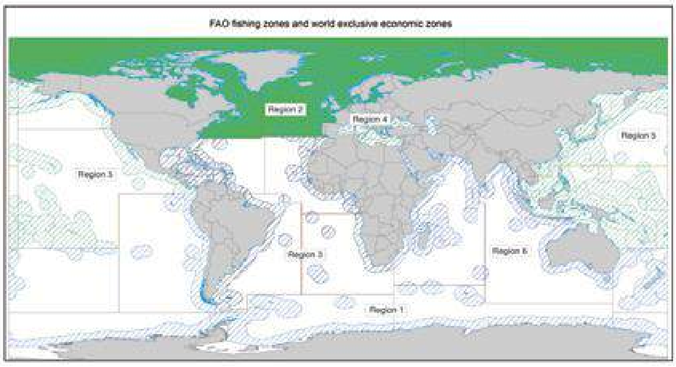
North Atlantic and Arctic Ocean

(FAO 21, 27, 18)



Gunnar Haraldsson[1], Sam Dupont[1], Bernard Avril, Manuel Barange, John Baxter, Richard Bellerby, Courtney Hough, Hans Poertner, Katrin Rehdanz and Stéphanie Reynaud[2].

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[1] Group leader. [2] Facilitator.

See map in Annex 1, p. 131.

EXECUTIVE SUMMARY

The North Atlantic and Arctic Ocean region includes Food and Agriculture Organization fishing regions 21, 27 and 18. Possible impacts of ocean acidification on fisheries and aquaculture in the region differ between northern and southern parts of the North Atlantic, and are higher in the North in terms of degree of acidification and organisms and ecosystems affected. Fishing activities are carried out by coastal countries of the region and international fleets in the high seas. In most countries bordering the region, fishing is a small part of the national economy; however, it is of great economic and cultural importance locally. Iceland, the Faroe Islands and Greenland have exceptionally high national fishery dependence for the region. Based on experimental results, the sensitivities of economically-relevant phyla differ with corals, echinoderms, molluscs and fishes being more sensitive than crustaceans. Calcification is the process most uniformly affected by ocean acidification. The negative impact of ocean acidification on fish behaviour and the sensitivity of calcifying invertebrates may make these groups particularly vulnerable to the ocean changes expected in the North Atlantic and Arctic in the future.

Capture fishery production within the region is estimated to be $8 billion, with the majority (55%) based upon crustaceans, which appear to be less sensitive to acidification effects. The remainder of fishery catch includes twelve percent molluscs and thirty three percent categorized “other”, predominantly fish. The industry supports 325,000 employees in harvesting (63%), processing (29%) and aquaculture (8%). The North Atlantic region is dependent on imports for many fishery products, and therefore has the added vulnerability of impacts that may occur in the supply regions.

The combined effects of ocean acidification, warming, and deoxygenation have significant implication for change in the population structure of marine resources. Based on the limited available ecosystem level data, a theoretical framework data suggests mixed positive and negative intermediate-term direct and indirect effects of increased global CO_2. Increasing ocean surface temperature is a primary driver of geographical relocation of highly mobile species, such as fish populations. In some cases, this may benefit North Atlantic fisheries for a period of time, as fish species shift in biogeographic range toward the higher latitudes or deeper waters. However, ocean acidification will reduce fitness for many species, and have consequences for overall abundance. Decreased Arctic ice cover due to warming will exacerbate effects of ocean acidification in northern waters. Expanding areas of oxygen deficiency will limit liveable habitat. Ecosystem resilience will be reduced in hypoxic, acidified waters of a high CO_2 ocean. An important ecosystem in this region is the deep-sea habitats of cold-water corals, which are known for high local biodiversity. Preliminary experimental data indicates cold-water corals may be able to adapt or acclimate to limited decreases in ocean pH. In the longer term, the shoaling of the North Atlantic aragonite saturation horizon threatens to expose the majority of cold water coral reefs to corrosive under-saturated conditions before the end of the century.

1. THE SPECIFICITIES OF THE REGION

1.1. Geography

The North Atlantic Ocean lies between the American continent in the west and European and North African continents to the east. It covers FAO fishing zones 18, 21 and 27 (see map).

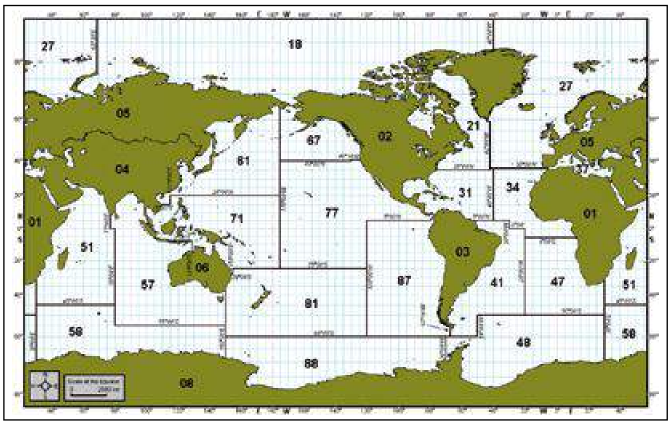

Figure 1.

FAO map of fishing areas.

It should be noted that when discussing possible impacts and possible mitigation of ocean acidification on fisheries and aquaculture, the situation between the northern part and the southern part of the North Atlantic is quite different in terms of the degree of acidification, which is higher in the North, and in terms of the organisms and ecosystems affected. The northern part of the North Atlantic is boarded to the west by Canada and the United States, while the eastern part is adjacent to the European continent. This has a profound effect on all economic analyses concerning the effects, and possible mitigation, of ocean acidification on fisheries and aquaculture in the area; the reason being that coastal countries in the region are developed industrialized countries. In most of these countries (with the notable exceptions of Iceland, Greenland, and the Faroe Islands) fisheries play but a small part in the national economy although fisheries have economic importance in local areas. Fishing activities in this area are not only carried out by coastal countries but also international fleets especially in the high seas.

1.2. Main stressors

Information available on the direct impact of climate change drivers including ocean acidification on fish, crustaceans, mollusks and echinoderm species of commercial importance indicates that temperature is presently the key driver of effects on marine ecosystems in general and specifically these organism groups. A meta-analysis of global observations shows that organisms track their preferred temperature ranges and as these temperatures move poleward or to deeper waters organisms tend to move with them (Poloczanska *et al.*, 2013). These large scale biogeographic displacements are projected to continue over the next decades and as thermal ranges are species specific, these displacements will also lead to changes in community compositions and species interactions with as yet unclear outcomes (Pörtner *et al.*, 2014). At the same time species display specific sensitivities to other drivers such as ocean acidification. A recent metaanalysis of experimental studies identifies differences in the sensitivity of economically relevant animal phyla, with corals, echinoderms, molluscs and fishes being more sensitive than crustaceans (Wittmann and Pörtner, 2013). The findings for the invertebrate phyla resemble palaeo-observations on the responses of these phyla to ocean acidification. Palaeo-references do not exist for fishes. Calcification stands out among the processes most uniformly affected by ocean acidification (Kroeker *et al.*, 2013).

Fish

According to the metastudy by Wittmann and Pörtner (2013) behavioural studies in the laboratory and at volcanic seeps (e.g. Munday *et al.* 2014) indicate high vulnerability of fishes, as high as that of the most sensitive invertebrate groups. These results contrast earlier findings where studies of vegetative physiological functions indicate high resilience of physiological rates and their regulation (Ishimatsu *et al.* 2008). It remains to be explored whether these behavioural disturbances persist long-term or are alleviated during trans-generational adaptation. Recent studies of fish larvae documented negative effects of ocean acidification on a sensitive fraction of early larvae whereas others remained unaffected (e.g. Frommel *et al.* 2012), likely as a consequence of large phenotypic variability in the larval population. It remains largely unexplored whether the selective forcing exerted by ocean acidification leads to detrimental effects at the population levels or even supports accelerated evolution of resistance. The ocean acidification signal adds to the one of temperature. Preliminary data support the generalized hypothesis that elevated CO_2 exacerbates the sensitivity to extreme temperatures (Pörtner and Farrell 2008). Then the large scale redistribution of fish stocks projected by the mid-century (to higher latitudes and greater depths, Pörtner *et al.*, 2014) will be affected. Rising CO_2 levels will reduce the fitness of individual species under extreme temperatures at their Southern distribution limits causing biogeographic ranges to shrink with potential consequences for their overall abundance. Expanding oxygen deficiency in ocean mid-water layers goes hand in hand with progressive CO_2 accumulation and acidification. Fishes in those hypoxic and hypercapnic areas will also be found less resilient to the warming trend and experience habitat contraction under the influence of the three drivers (Pörtner *et al.*, 2014).

Crustaceans

The metastudy clearly shows that the diverse crustacean species (copepods, shrimps, crabs, lobsters, krill, etc) are less responsive to ocean acidification than the more sensitive invertebrates (bivalves among molluscs, sea urchins among echinoderms), some even benefit under elevated CO_2. Larval stages, especially the megalopa stage represent a bottleneck of environmental sensitivity. The synergistic interactions of warming and elevated CO_2 were demonstrated to be effective in crustaceans suggesting that their biographical ranges will also be constrained under the synergistic effects of warming and ocean acidification (e.g. Walther *et al.*, 2009).

Bivalves (oysters, mussels)

The effects of ocean acidification on bivalves are variable among species and even within the same species, precluding the drawing of a general picture. The sensitivity level and distribution among mollusks overall is similar to that of the echinoderms or corals (Wittmann and Pörtner, 2013). The available literature suggests that while detrimental effects on adults remain uncertain, the most sensitive life-history stage seems to be the larvae, with a large majority of studies on this critical stage of development revealing negative effects (Gazeau *et al.* 2012). Among bivalves, mussels appear to be fairly resilient and can even thrive in low pH waters (e.g. Thomsen *et al.* 2012) but oysters are on the first line of seafood species potentially impacted by ocean acidification. Impact of acidification on oysters fitness is mostly negative (85% of the studies) with an increased mortality and reduced growth. The first consequences on oyster production are already visible today. In hatcheries located on the Northern west coast of the US, a US$ 270 million industry, there has been a decline in the survival of oyster larvae since 2005, which appears to be connected to near-shore acidification (Barton *et al.* 2012).

Sea urchins

Most echinoderms calcify as adults and larvae, and consequently echinoderms are one of the primary targets for ocean acidification research. The many available studies show that echinoderm responses are generally highly species-, population and individual-specific, ranging from likely species extinction, direct or indirect negative effects (such as delay in development), to positive effects (see Dupont *et al.*, 2010 for review). The green sea urchin *Strongylocentrotus droebachiensis* has become a valued commodity and it is now extensively fished and cultured for its roe in Northwest Atlantic. It is also one of the best studied sea urchin species showing that ocean acidification is likely to impact their long term survival. For example, long term exposure to ocean acidification and trans-life-cycle effects may translate into a 100 time increased mortality of their juveniles. It is unlikely that ocean acidification will have a major negative effect on these taxa within the next decades (in particular compared to other drivers). However, some effects are likely in bivalves and urchins by 2100.

Overarching information

1/ We can use the available information on mechanisms to develop a theoretical framework to understand the impact of both ocean acidification and temperature on key species (e.g. Pörtner & Farrell 2008). The exact mechanisms of how elevated CO_2 and temperature interact may depend on the phylogenetic group. In animals elevated CO_2 seems to interfere with the capacity of oxygen supply systems to cover the oxygen demand of the organisms.

2/ The conclusions are based on the limited available evidences. Many key parameters are still poorly investigated, including:

— *Most experiments are short term and do not consider adaptation potential / acclimation (e.g. for mussels and urchins, Sunday* et al., *2011; Dupont* et al., *2012), or selection of resistant genetic strains (Lohbeck* et al., *Sunday* et al.*).*

— *Most studies focus on a single life-history stage and do not consider carry-over, maternal effects (e.g. for oysters, Parker* et al., *2012).*

— *Indirect effects can occur through ecological interactions.* Ocean acidification consequences for food web interactions are, still poorly known. Indirect ocean acidification effects can be expected for consumers by changing the nutritional quality of their prey (Rossol *et al.* 2012).

Ecological interactions. A negative effect on food quantity for fish (pteropods) has been reported (Comeau *et al.* 2009). Pteropods (shelled pelagic mollusks, commonly referred to as “sea butterflies”) play a significant role in the food web of various ecosystems and in the cycling of carbon. They could be very sensitive to ocean acidification due to their aragonitic shell. Comeau et al (2009) have shown that the calcification of pteropods in culture under controlled conditions exhibits a 28% decrease at the pH value expected for 2100 compared to the present pH value. This result supports the concern for the future of pteropods in a high-CO_2 world, as well as of those species dependent upon them as a food resource. A decline of their populations would likely cause major changes to the structure, function and services of polar ecosystems.

Habitat destruction. Cold-water corals (CWC) are amongst the most three-dimensionally complex deep-sea habitats known and are associated with high local biodiversity. However, their remoteness and the relatively short history of ecological research mean that we have little information on how these ecosystems will fare in the face of predicted future climate change, and particularly ocean acidification. Available data indicate that, possibly as a result of their adaptation to CO_2-enriched mid-water layers the sensitivity of cold-water corals to elevated CO_2 levels is somewhat less than in warm-water corals (Pörtner *et al.*, 2014).

— *Most studies are considering ocean acidification as a single stressor and do not take into account natural variability and other modulating parameters (Dupont & Pörtner 2013).*

1.3. Biological and chemistry characteristics

There is now no doubt that the great climate service that the ocean provides by absorbing more than 90 % of the excess heat and a large fraction of carbon dioxide from the atmosphere is causing ocean acidification. Global measurements show an increase in dissolved CO_2 concentration that is causing a reduction in seawater pH and a reorganization of the speciation of total carbon dioxide. The major effect is mirrored in a reduction in the carbonate ion concentration, and thus in the stability of $CaCO_3$. Such changes also occur in the body fluids of organisms and at calcification sites, depending on the capacity of the organisms to tolerate or compensate for such effects.

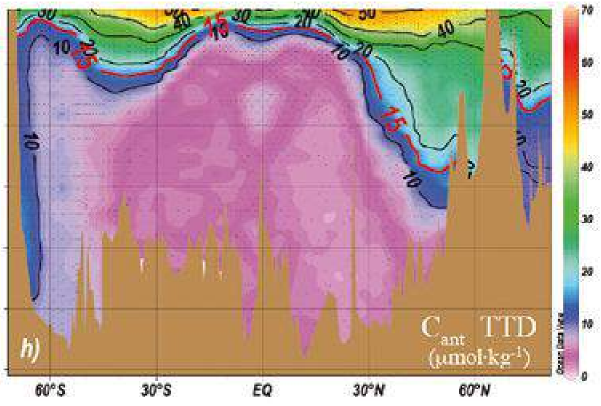

Figure 2.

Atlantic anthropogenic carbon distributions showing that the North Atlantic is the only major basin where ocean acidification has penetrated the water column and is therefore potentially influencing "all" systems (Vázquez-Rodríguez *et al.,* 2009).

The North Atlantic is the largest reservoir of anthropogenic CO_2 (Vázquez-Rodríguez *et al.*, 2009; Khatiwala *et al.* 2013). Time series measurements show consistent increase in CO_2 and concurrent reductions in pH. Anthropogenic carbon concentrations are greatest in the surface and, following intermediate and deep-water formation, the ocean acidification is now seen throughout the entire water column.

The surface Arctic Ocean is supplied with waters of high CO_2 from the south through the Nordic Seas and the Bering Strait. These acidification highways carry waters high in CO_2 deep into the surface and intermediate Arctic Ocean. Waters of the Arctic are, generally, already low in carbonate ion, have a low buffer capacity and thus are most susceptible to ocean acidification (Bellerby *et al.*, 2005; Steinacher, 2008). Ocean warming and acidification play different, sometimes complementary, often counteracting roles in the changing speciation and pH response of the Arctic (Orr *et al.*, 2005; Steinacher *et al.*, 2008; Denman *et al.*, 2011; Bellerby *et al.*, 2012).

The main basin-wide driver of ocean acidification in the Arctic is the uptake of anthropogenic CO_2 which is now not only being transferred from the south though the acidification highways of the Nordic Seas and the Bering Strait but being enhanced by reduced ice cover and thus more direct air-sea transport. Furthermore, freshening of the ocean, through ice melt and increased fluvial inputs is reducing the $CaCO_3$ saturation state as it lowers the ion concentrations. Warming of the Arctic complements the CO_2 induced ocean acidification further, yet counteracts the falling saturation state as $CaCO_3$ stability increases with increasing temperature.

Our present understanding of the evolution of ocean acidification for the North Atlantic and, especially, the Arctic Ocean is still poor. Although model projection of future acidification are based on very few our understanding is sufficient to identify that critical thresholds will be reached for geochemical and physiological processes that highlight the sensitivity of the regions to increasing CO_2.

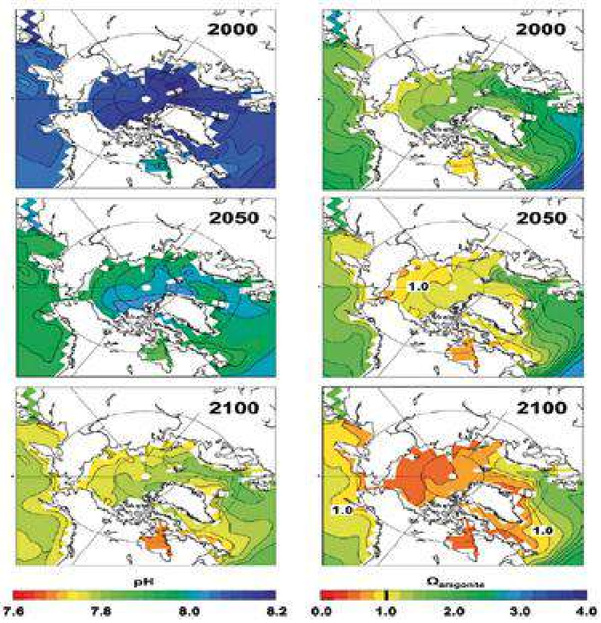

Figure 3.

Arctic Ocean acidification from an earth system model of the kind used to inform present bioeconomic models (Denman *et al.,* 2010).

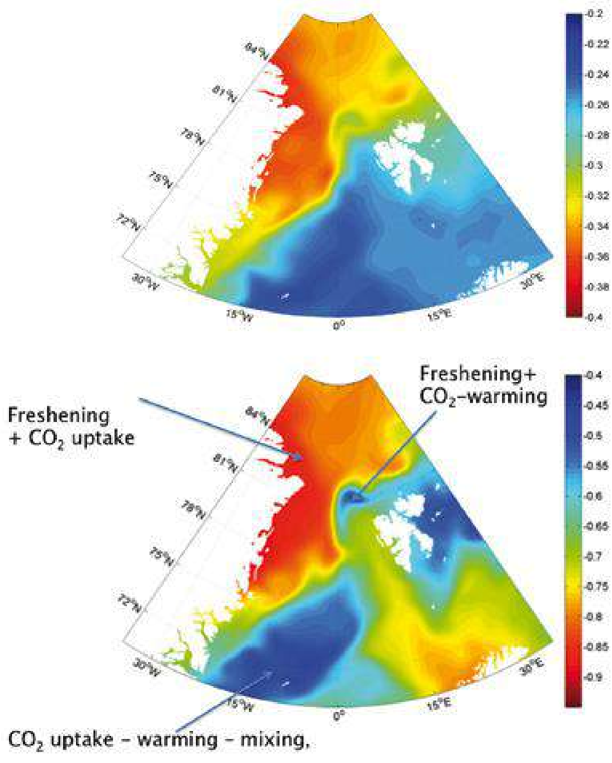

Figure 4.

Regionally downscaled Nordic Seas and Arctic ocean acidification simulations. Centennial (2100-2010) changes of pH (top) and Ωarag (bottom) (Bellerby *et al.,* 2012).

2. BIOLOGICAL IMPACTS OF OCEAN ACIDIFICATION

Lophelia pertusa is the most widespread CWC species, frequently found in the North Atlantic.

To date, the responses of calcification rates of *Lophelia pertusa* to ocean acidification are contradictory:

- A strong decrease by 30% (Maier *et al.* 2009) on short-term (one week) high CO_2 exposure. The effect was stronger for fast growing, young polyps (59% reduction) than for older polyps (40% reduction) which implies that skeletal growth of young polyps will be influenced more negatively by ocean acidification. Nevertheless, *L. pertusa* revealed a positive net calcification at an aragonite saturation state (Ωa) below 1, which may indicate some adaptation to an environment that is already relatively low in Ωa.
- The maintenance of calcification rate (Hennige *et al.,* 2013), associated with a decrease in respiration rate indicates an energetic imbalance, likely facilitated by utilization of lipid reserves.
- An acclimation to acidified conditions in long-term (six months) incubations, and even slightly enhanced calcification (Form & Riebesell, 2012).

2.1. Identification of the major threats: pCO$_2$, Ω

The aragonite saturation depth or 'horizon' (ASH) is predicted to become shallower, making it more difficult for calcifying organisms near this depth to maintain their structures, thus affecting net reef growth. CWC are under particular threat as they inhabit a large bathymetric range, and are closer to the ASH. Only 5% of CWC are found below the ASH at present, as net calcification below the ASH would require considerable energetic input at the detriment of other energetic processes. In the North Atlantic, observations show that the saturation horizon has shoaled 80 - 400 m since preindustrial times (Feely *et al.* 2004) and might shoal another 2,000 m until the end of this century as projected by models (Orr *et al.* 2005), exposing the majority of reefs to corrosive waters. In view of this, CWC reefs are considered the ecosystem most vulnerable to ocean acidification.

Ocean acidification consequences for food web interactions are poorly known. Indirect ocean acidification effects could be expected for consumers by decreasing food quality of their prey (Rossol *et al.* 2012), or food quantity. For example a decline of the population of pteropods would likely cause major changes to the structure, function and services of polar ecosystems (Comeau *et al.* 2009). There is, however, no indication of widespread decrease in food quantity or quality as a result of ocean acidification.

3. ECONOMIC IMPACTS OF OCEAN ACIDIFICATION

3.1. General economic considerations

Fisheries and aquaculture in North America and coastal European countries represent a small fraction of the national economies, with the exceptions of Greenland, Iceland and the Faroe Islands. Although these industries are relatively small in the national economic context, they are of major regional importance in many coastal areas and their political, social and cultural importance is far more important than the percentage of GDP would suggest. A "guesstimate" suggests that fisheries amount to less than 1% of GDP for this region as a whole[1].

Trends in catches are not necessarily a simple function of species abundance, not even over long time periods, so data on trends on landings may not yield much information on actual or predicted effects of ocean acidification or other changes in the environment.

Research suggests that ocean acidification may affect shellfish and fish production quite differently. While most studies indicate a negative economic impact on global shellfish (Cooley and Doney, 2010, Narita *et al.* 2012) production, the effect on fish production (growth and survival) can even be positive (see Armstrong, *et al.*, 2012 for a study on Norway). This means that the share of fish production vs shellfish production can be crucial to an analysis of the impacts and possible mitigation of ocean acidification.

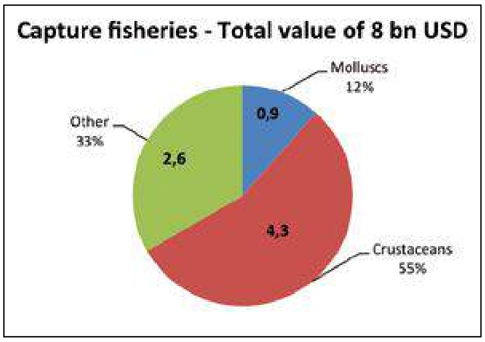

Figure 5.

Source: Sea around us project.

3.2. Employment

It is somewhat difficult to estimate the number of people engaged in fishing, either as a full-time, part-time or recreational activities. Existing data are incomplete and do not include people working in other parts of the value chain. Furthermore, it can be difficult to estimate the number of jobs related to fisheries, along the entire value-chain. The following figure is based on OECD data[2]. The total number of people working in fisheries are around 325,000 which is an underestimation but pro-

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[1] http://www.cfp-reformwatch.eu/pdf/002.pdf

[2] OECD (2012).

vides an idea about the order of magnitude[3]. It should be kept in mind that some important fishing countries only submitted partial data or no data at all.

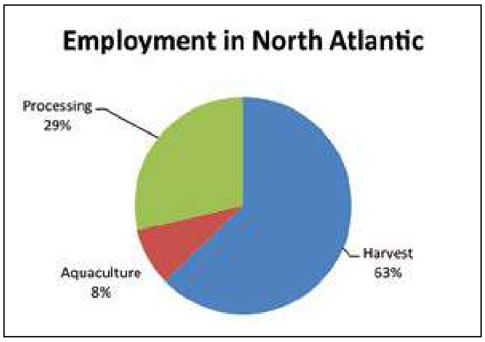

Figure 6.

Source: OECD (2011).

3.3. Market considerations

When evaluating the effect of ocean acidification on human welfare it must be noted that the developed economies of North America and Europe[4] are relevant import markets for fish and other seafood. Hence, the welfare of people living in these countries – particularly dietary – may be strongly affected by what happens in other areas of the world, both with regards to production and changes in trade patterns. Many coastal communities depend on fisheries and aquaculture, either as a direct activity or through providing services (e.g. processing, logistics). The economic growth of many emerging markets has changed the picture somewhat. As these economies grow and incomes rise, they will stop being primarily export markets to richer countries but become important consumers and importers themselves, even if prices rise for fish and other seafood. The seafood processing sector in developed countries is heavily dependent on imports for its activity[5]. Geopolitical and global economic trends may therefore have huge impacts on the welfare effects of ocean acidification in western developed economies.

3.4. Effect of ocean acidification on fisheries

Ocean acidification can affect fisheries and aquaculture through two channels. It may change the abundance of species in specific areas and/or the distribution of species between different areas. In response to warming in both hemispheres, species will move to higher latitudes or deeper waters following their preferred temperatures. High, especially Northern latitude regions are projected see the arrival of new species while species diversity in low latitude areas becomes impoverished. This opens up a range of possibilities concerning the welfare effects. Such changes might benefit both regions (example, crustaceans for cod situation in Canada), benefit one but not the other, or be negative for both.

Neighbouring countries can have different fisheries, meaning ocean acidification can have different economic consequences. To take an example, the shrimp fishery in Greenland is of great economic importance while neighbouring Iceland is much more reliant on the cod and other finfish species. Changes in environmental factors will also affect the relative competitiveness of different aquaculture producers, and it can be expected that companies will react to such changes by relocating their operations, shutting down and/or lead to changes in what species are farmed.

Armstrong *et al.* (2012) present estimates of the effect of ocean acidification on fisheries and aquaculture in the North Atlantic. The numbers are based on meta-studies (Hendriks *et al.*, 2010, and Kroeker *et al.*, 2010). The numbers represent effects on growth and effects on changes of survival (see table). The time horizon is 100 years. Two scenarios are presented; best case and worst case. The effects are assumed to be linear over time.

Table 1.

Scenarios for effects of ocean acidification on fisheries and aquaculture in the North Altlantic.

	Best case	Worst case
Fish	18.35% increase in growth, no changes in survival	1.84% increase in growth, no changes in survival
Bivalves / molluscs	2.7% increase in survival and 18.79 increase in growth	59.44% reduction in survival and 39.49% reduction in growth
Crustaceans	5.58% increase in survival and 17.64% increase in growth	26.55% reduction in survival and 2.64% reduction in growth

Armstrong *et al.* (2012) use these numbers to estimate the net present value of the aggregate economic loss. The outcomes differ not only between the two different scenarios but also with the discount rate chosen. Interestingly, given these numbers and assumptions, ocean acidification has a positive effect on fish values, under both scenarios.

4. POLICY RECOMMENDATIONS

Given the overall small share of fisheries in North Atlantic economies, there does not seem to be an imminent economic crisis caused by ocean acidification. Notable exceptions are Iceland and Greenland, whose dependency on fisheries increases national risks of global change effects. Although fisheries usually do not play a big role in North Atlantic economies in general, they are extremely important in many smaller local areas, both with regards to industrial and small scale fisheries as well as recreational fishing and aquaculture. Therefore, adaptive management considerations may be called for in specific areas and for specific fisheries.

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[3] This includes the EU countries, Norway, Iceland, Canada and the USA.

[4] Exceptions : Norway, Iceland, Faroes who are net exporters.

[5] In EU, AIPCE estimates this to be 90% (AIPCE 2012).

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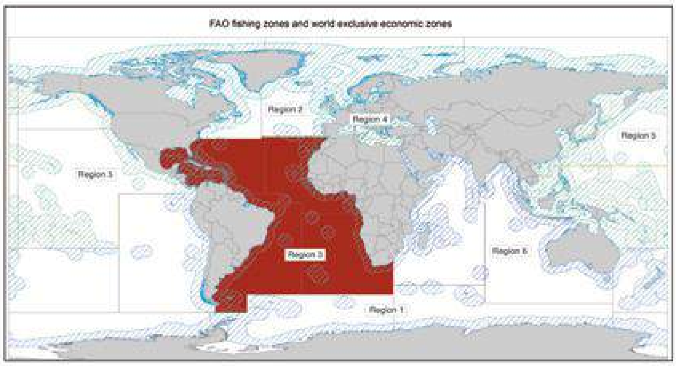
Central and South Atlantic Region

(FAO 31, 34, 41, 47)



Sarah Cooley[1], Anthony Charles[1], Andreas Andersson, Alexander Arkhipkin, Vicky Lam, Juan Carlos Seijo and Jean-Pierre Gattuso[2].

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[1] Group leader. [2] Facilitator.

See map in Annex 1, p. 132.

EXECUTIVE SUMMARY

The Central and South Atlantic Oceans can be best characterized as a collection of sub-regions with distinctly different terrestrial influences and oceanographic circulation, as well as different fisheries harvests and human communities that depend on them. Ocean warming and acidification affect the entire region. Coastal waters also experience impacts from nearby landmasses and human communities, such as pollution from agricultural fertilizer, nitrogen and sulfur emissions from fossil fuel combustion and agriculture, and decreasing salinity from Antarctic ice melting. All of these impacts can add to acidification directly or contribute to eutrophication and subsequent deoxygenation, which may worsen the response of marine organisms to acidification. In the four FAO fishing areas that make up this region, 32%-57% of the fish stocks have no room for further expansion by commercial fishing. Overall catch trends across the region have been level or declining in the past two to three decades. Of the taxonomic groups most likely to be directly affected by ocean acidification, finfish, mollusks, crustaceans, and corals provide the most benefits to fisheries in the Central and South Atlantic regions. Given the negative response of bivalve mollusks to ocean acidification in laboratory studies, it seems that artisanal (e.g. yellow clam *M. mactroides*, Uruguay), small scale/semi-industrial (e.g., queen conch *Strombus gigas,* Caribbean) and bivalve aquaculture fisheries (e.g. Eastern oyster *C. virginica,* Brazil) are regional fisheries that are more likely to be impacted by OA. Changes or loss in physical habitat structure as a result of OA could also negatively affect individual species, such as those living among rhodolith beds (i.e., coralline red algae) in the eastern Caribbean and off the coast off Brazil. So far there is no evidence that major open ocean finfish fisheries in this area (e.g. hake, tuna, billfish, sardines, anchovy) will be directly impacted by OA, but current thinking suggests that ocean acidification will most likely affect finfish fisheries through changes in trophic relationships, such as those related to a decrease in overall food availability and/or the flow of energy among trophic levels.

The Central and South Atlantic region is bordered by many nations whose per capita GDP ranks in about the lower two-thirds of the world's nations. Many nations bounding this region also have less resilient human communities for withstanding possible losses of natural resources. Given the strong probability that OA will act hardest on near-shore and smaller scale fisheries in this region, it has the potential to worsen food distribution inequality that already exists and remove an important source of revenue to coastal communities in Central and South Atlantic. If ocean acidification and temperature rise result in range shifts of vulnerable yet economically important species, small-scale fishers will require local management strategies that are flexible enough to allow them to target a changing variety of accessible species using different gear types. Helping subsidize changing gear, retraining local fishers for other occupations, or helping identify and cultivate nutritional alternatives will likely be necessary for many local jurisdictions in the Central and Southern Atlantic, given the relatively low regional income and social resilience in many bordering nations. Large-scale fishers, on the other hand, may need policies that are geographically flexible that allow them to go farther afield for the same species. The dissimilarity of these two fishery categories and their responses points to the need for policy and adaptation research that address different scales. Nevertheless, close coordination among local, regional, and national authorities as well as user groups and researchers has been demonstrated to yield quick, effective responses to ocean acidification events elsewhere. Involving end users in decision-making and governance will lead to more effective outcomes.

1. THE SPECIFICITIES OF THE REGION

1.1. Geography

The Central and South Atlantic Oceans are bordered by the South American and African continents on the east and west sides, which form an irregularly shaped basin. This region (which encompasses FAO areas 31, 34, 41, 47; Figure 1) can be best characterized as a collection of sub-regions that have distinctly different terrestrial influences and oceanographic circulation, as well as different fisheries harvests and human communities that depend on them.

The most northerly sub-region, the north end of the Central Atlantic Ocean, includes the southern half of the North Atlantic Subtropical Gyre, the Caribbean ocean and Gulf of Mexico. This region has an overall wind-driven clockwise circulation and a western boundary current, the Gulf Stream, which transports water and heat from the Caribbean and the Gulf of Mexico northward (Figure 2). On the southeastern side of the North Atlantic gyre, or the northeastern border of the portion of the Central Atlantic under study here, strong upwelling occurs.

The Caribbean Sea and Gulf of Mexico have separate circulation regimes due to their semi-enclosed nature. The Caribbean Sea is characterized by westward currents flowing from the Lesser Antilles to the Gulf of México (Alvera-Azacarate, 2002). These currents are fed by waters of South Atlantic origin entering through southern Lesser Antilles as well as waters of North Atlantic origin that recirculate southwestward and enter the Caribbean through the Lesser Antilles (Johns *et al.,* 2002). The flow enters the Gulf of Mexico as a narrow boundary current that hugs the Yucatan Peninsula (Fratantoni 2001). This Yucatan Current flows into the Gulf of Mexico through the Yucatan Channel. It eventually separates from the Campeche Bank and becomes the Loop Current. The Loop Current then becomes the Florida Current as it exits the Gulf of Mexico through the Straits of Florida (Molinari and Morrison 1998). South of these sub-regions is the Equatorial Atlantic Ocean, which is marked by a complex equatorial current system (Figure 3) and tropical temperatures and ecosystems. The net effect of this is to drive strong seasonal upwelling along the West African coast in boreal summer when alongshore winds are strongest. Seasonal upwelling appears near Dakar, Abidjan, and from Cape Lopez to Cape Frio (Figure 4). Year-round upwelling occurs more to the north, north of Cape Blanc, and more to the south, south of Cape Frio.

The next most southerly sub-region is the South Atlantic Subtropical Gyre, which is marked by temperate conditions and strong upwelling on the eastern boundary at the Benguela Current. Return flow along the southern end of the subtropical region is west to east at the edge of the Southern Ocean as part of the Antarctic Circumpolar Current System.

Several of the largest rivers in the world, including five of the top ten in terms of volume discharge, flow into the Central and Southern Atlantic (Van der Leeden *et al.* 1990). This provides large quantities of fresh water, terrestrial nutrients, and organic material to the nearshore zone. Plumes of very large rivers like the Amazon, Orinoco, and the Congo travel far from the nearshore zone and enrich biological production well offshore (Signorini *et al.,* 1999).

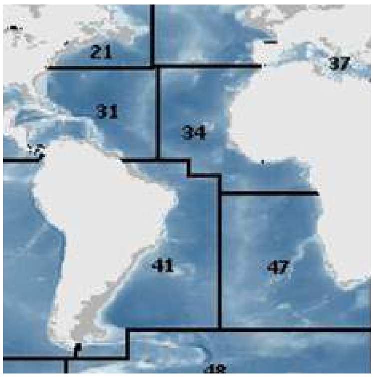

Figure 1:

Central and South Atlantic, with FAO fishing regions marked.

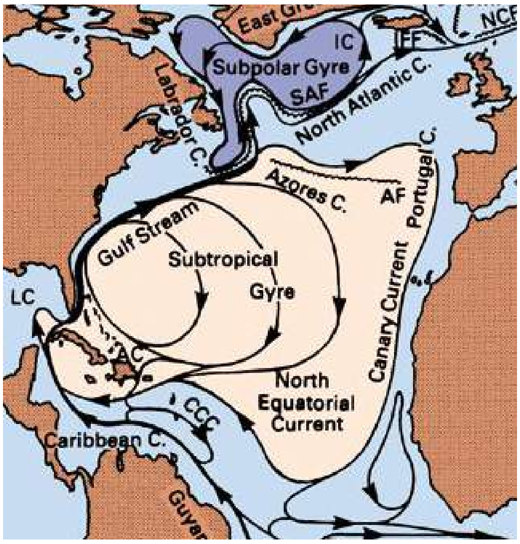

Figure 2:

Overview of the general circulation and major currents in the Central and North Atlantic ocean overlapping with FAO fisheries areas 31 and 34.
From Tomczak and Godfrey (2003).

1.2. Main stressors

Biogeochemical stressors

All of the sub-regions of the Central and South Atlantic are experiencing major environmental changes due to human activity. Rising temperature and atmospheric carbon dioxide are causing ocean warming and acidification in most places. Coastal waters also experience impacts from nearby landmasses and human communities. Nitrogen and sulfur emissions from fossil fuel combustion and agriculture have been shown to add slightly to ocean acidification, especially in

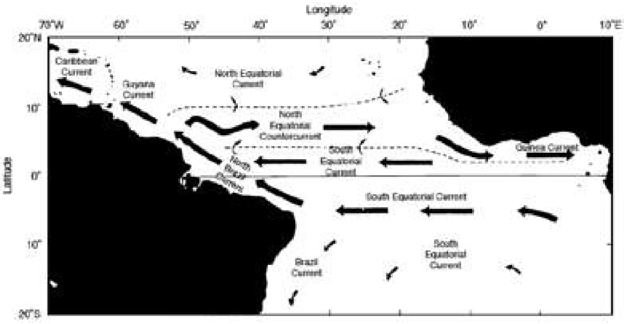

Figure 3:

Schematic of the major surface currents of the equatorial Atlantic Ocean during July-September. From January-May the North Equatorial Countercurrent disappears, causing the surface flow to move westward in the whole region.
From Philander (2001).

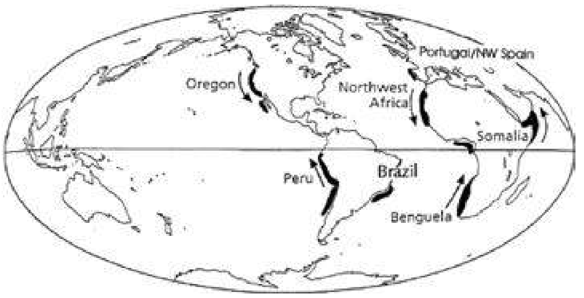

Figure 4:

Major coastal upwelling centers around the world.
From Peterson 1998.

coastal regions and more strongly in the Northern Hemisphere (Doney *et al.* 2007). This can add to acidification in some parts of the region, or it can contribute to eutrophication and subsequent deoxygenation. Other human activities, especially fishing, in the Central and South Atlantic, place a great deal of stress on coastal resources. In the four FAO fishing areas that make up this region, 32%-57% of the fish stocks have no room for further expansion by commercial fishing (FAO, 2005; Freitas *et al.* 2008). Fish stocks are not well quantified in these areas, as it is still unknown whether 39-56% of the fish stocks have room for expansion or not (Freitas *et al.* 2008).

At the same time, these sub-regions also experience various local-scale impacts resulting from human activity, including pollution from agricultural fertilizer or other manmade chemicals, atmospheric ozone depletion, decreasing salinity due to Antarctic ice melting, and overfishing. The type and extent of these impacts varies widely across the Central and South Atlantic region, but most often, these stressors affect the coastal and nearshore zones more heavily than offshore areas. The composite stress on marine ecosystems tends to be greatest for nations along the eastern boundary of this region (i.e., the West Coast of Africa), given the mixture of environmental and human concerns overlapping there (www.oceanhealthindex.org, Halpern *et al.* 2012). In particular, the Ocean Health Index is low for countries in the Central and South Atlantic because of low scores related to food provision, natural products, coastal protection, coastal livelihoods and economies, and sense of place, and in very specific areas along the West African coast, also because of low scores regarding tourism and recreation, and carbon storage (www.oceanhealthindex.org).

Fishing pressure

The FAO's State of Fisheries and Aquaculture publication (FAO 2012) indicates that in terms of overall catch trends, (1) there has been a strong steady decline in the southeast Atlantic; (2) a decline is also evident in the western central Atlantic; (3) the southwest Atlantic, while arguably having somewhat level catches over a 20-year period (at about 2 million tonnes per year), shows indications of a decline in the past 10 years; and (4) the eastern central Atlantic has had steady or slightly increasing (albeit fluctuating) catches over the past 30 years (Figure 5).

FAO (2012, p.58) considers the Southeast Atlantic to be "a typical example of the group of areas that has demonstrated a generally decreasing trend in catches since the early 1970s."

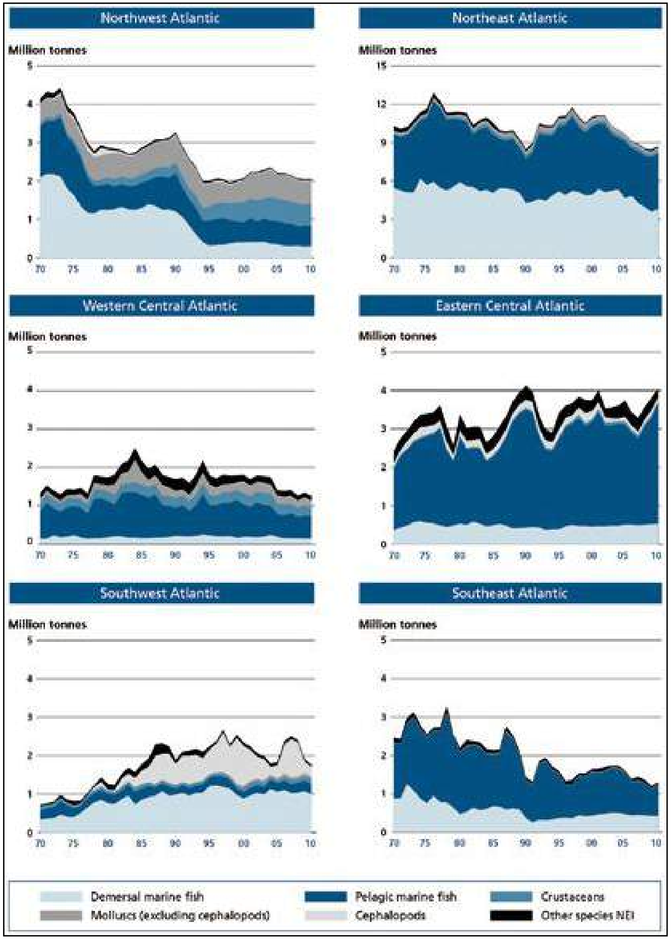

Figure 5:

Capture fisheries production in marine areas.
(Excerpted from FAO 2012).

Specifically, it is noted that the area "produced 3.3 million tonnes in the late 1970, but only 1.2 million tonnes were recorded in 2009." Hake is considered to be "fully exploited to overexploited" despite some improvement in certain stocks. Southern African pilchard has declined, due to "unfavourable environmental conditions," while Southern African anchovy "has continued to improve." FAO (2012) particularly draws attention to Cunene horse mackerel, noting it "has deteriorated, particularly off Namibia and Angola, and it was overexploited in 2009," as well as "the perlemoen abalone stock [which] continues to be worrying, exploited heavily by illegal fishing, and it is currently overexploited and probably depleted."

As noted above, the Eastern Central Atlantic contrasts with the Southeast Atlantic in showing a better overall trend. The increase in the total production in this region in the last 3 years was mainly influenced by the activities of the distant-water fleet. However, FAO (2012, p.57) reports that most stocks are fully exploited or overexploited – specifically that the area "has 43 percent of its assessed stocks fully exploited, 53 percent overexploited and 4 percent non-fully exploited…" In this region, "small pelagic species constitute almost 50 percent of the landings" and "the single most important species in terms of landings is sardine (*Sardina pilchardus*) with landings in the range of 600 000–900 000 tonnes in the last ten years." It is noted that "most of the pelagic stocks are considered fully exploited or overexploited," "demersal fish resources are to a large extent fully exploited to overexploited in most of the area," and "some of the deepwater shrimp stocks seems to have improved and they are now considered fully exploited, whereas the other shrimp stocks in the region range between fully exploited and overexploited."

In Western Central Atlantic, the reduction in catch production in 2010 was mainly attributed to the oil spill in the Gulf of Mexico. Finally, FAO (2012, p.57) notes that in the Southwest Atlantic, "50 percent of the monitored fish stocks were overexploited, 41 percent fully exploited and the remaining 9 percent considered non-fully exploited." Specifically, "major species such as Argentina hake and Brazilian sardinella are still estimated to be overexploited, although there seem to be some signs of recovery for the latter. The catch of Argentina shortfin squid was only one-fourth of its peak level in 2009 and considered fully exploited to overexploited."

1.3. Biological and chemical characteristics

The Central and South Atlantic contains a variety of ecosystems, including pelagic, coastal/near-shore, upwelling, and coral reefs. Each of these have broadly varying biological and chemical characteristics, and the level of understanding about those also varies greatly. Hydrographic and chemical monitoring of many of these environments lag, for example, comparable environments in the North Atlantic, even though two key long-term oceanographic monitoring sites are located in this region. Despite the variety of ecosystems in the region, fishery harvests remain the most economically important service provided by the Central and South Atlantic.

In the central and South Atlantic, three long-term time-series datasets have been collected to monitor conditions in the open ocean. Bermuda Atlantic Time Series (BATS), Hydrostation S, and the European Station for Time Series in the Ocean (ESTOC) are located within the region defined as the Central Atlantic, providing extensive data on environmental trends and biogeochemical properties in this region. Hydrostation S was established in 1954 and an almost continuous record of temperature, salinity and dissolved oxygen has been maintained. Sea surface temperature shows large variability on seasonal and decadal timescales, with a small, but detectable secular increase over time (Figure 6).

Seawater CO_2 parameters have been measured at BATS (combined with Hydrostation S) since 1983 and at ESTOC since 1995. The record at BATS shows a consistent increase in surface seawater pCO_2 tracking the observed increase in the atmosphere (Figure 7; Bates *et al.*, 2012**).** Surface seawater total dissolved inorganic carbon concentration (DIC) has increased by 1.53±0.12 mmol kg^{-1} yr^{-1}; pH has decreased at a rate of -0.0016±0.00022 pH units per year, and the saturation state with respect to aragonite has decreased at a rate of -0.01±0.0012 units per year (Bates *et al.*, 2012). The trends observed at the ESTOC are similar to those observed at BATS. Similar, shorter-term studies in the Caribbean have observed the same trends in this region (e.g., Gledhill *et al.*, 2009).

Environmental and chemical conditions in the near-shore regions are known to be more variable due to the effects of upwelling, river plumes, and terrestrial inputs (Doney, 2010). In addition, biological processes in shallow near-shore regions exert a strong effect on the seawater chemistry, which can either alleviate or exacerbate anthropogenic ocean acidification (e.g., Cai *et al.*, 2011). Upwelling and river plume-influenced regions in the Central and South Atlantic are characterized by high levels of dissolved nutrients, and host high primary production that attracts zooplankton and finfish. Large fisheries are traditionally located in these regions. In the Central Atlantic, fisheries harvests are especially high in the upwelling regions along the African continent (Figure 5), due primarily to harvests of sardine. In the Southwest Atlantic, major harvests include Argentine hake, Argentine shortfin squid, Patagonian grenadier, hoki and Brazilian sardinella. In the Southeast Atlantic, major exploited species include cape horse mackerel, hake, Pacific sardine and Southern African anchovy.

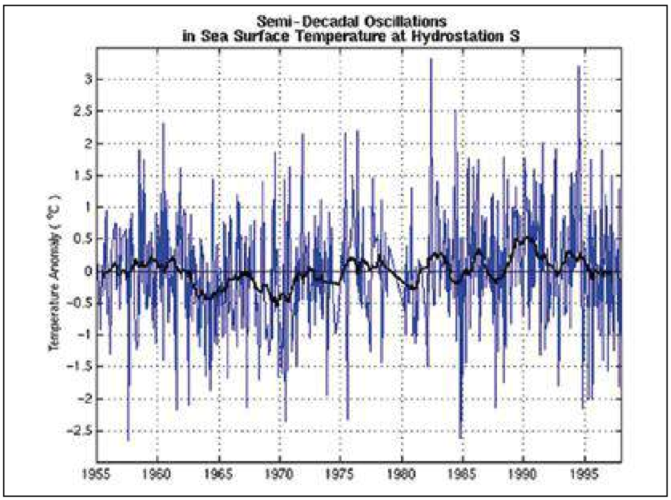

Figure 6:

Sea surface temperature at Hydrostation S between 1955 and 1998. The blue line shows the seasonally normalized SST anomaly and the black line shows the data with a low-pass filter emphasizing the longer term semi-decadal trend.
From http://www.bios.edu/research/hydrodata.html

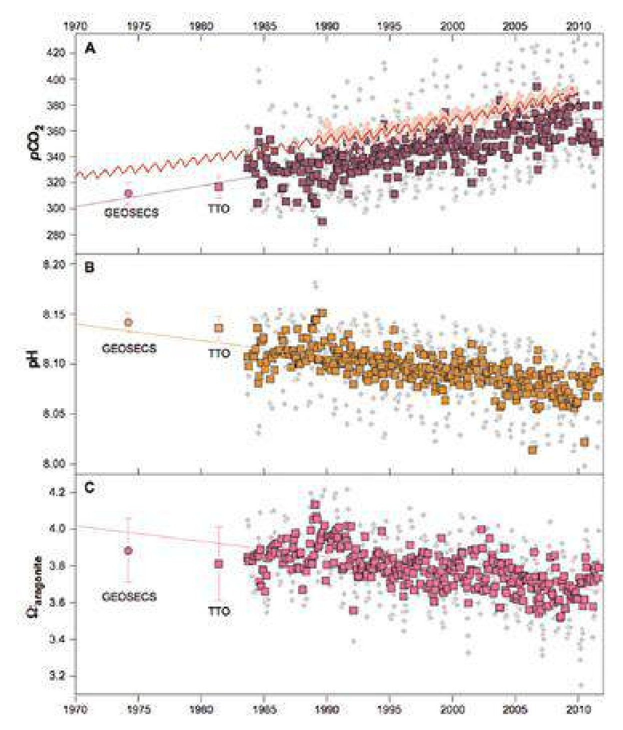

Figure 7:

Trends in atmosphere *p*CO_2 in Hawaii and Bermuda and surface seawater *p*CO_2, pH and saturation state with respect to aragonite measured at the Bermuda Atlantic Time-series Station (BATS) between 1983 until present and nearby measurements during GEOSECS and TTO in the 1970s and 1980s.
From Bates *et al.,* 2012**.**

In the Central Atlantic, tropical coral and mangrove ecosystems with high biodiversity host many nutritionally and economically valuable species. For example, Gulf menhaden and round sardinella are two major exploited fisheries in Central Western Atlantic. In Central Eastern Atlantic, European pilchard and sardine fisheries contribute to about 40% of the total landings in this region in the 2000s (Sea Around Us Project www.seaaroundus.org, Watson *et al.,* 2004). Open waters of the Central Atlantic are the main harvest areas of several species of tuna and swordfish. Frontal zones in the open waters concentrate abundant pelagic squid with commercial potential such as the orangeback squid (*Sthenoteuthis pteropus*) and the flying squid (*Ommastrephes bartrami*).

1.4. General socio-economic aspects of the area

The Central and South Atlantic region is bordered by a range of developing and developed nations, but the majority of bordering nations have smaller economies, and lower scores on social indicators. Per capita GDP based on purchasing power parity (PPP) varies widely for the nations bordering the Central and South Atlantic region. Nations in Eastern South America have somewhat higher GDP than those in West Africa; nevertheless, the nations bordering the entire ocean region have per capita GDP that ranks in about the lower two-thirds of the world's nations. Many nations bounding this region score low on worldwide governance indicators from Kaufmann *et al.* (2010), which indicate characteristics of the social system. Most of these indicators, which include voice and accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption, are in the 0th-50th percentile for nations bordering this ocean region.

2. BIOLOGICAL IMPACTS OF OCEAN ACIDIFICATION

Not many experiments have been performed to examine the effects of ocean acidification on most species native to the Central and South Atlantic regions. However, trends are emerging from the broader ocean acidification literature showing that calcifying algae experience negative effects on photosynthesis and growth; corals experience net negative effects on growth and calcification; mollusks experience net negative effects on survival and calcification; and crustaceans experience net neutral effects on growth, calcification, and slightly negative effects on survival (Kroeker *et al.,* 2010, 2013). In contrast, fleshy algae and seagrass may show positive responses in growth and photosynthesis (Kroeker *et al.,* 2010, 2013). Species from all of these taxonomic groups are socioeconomically important in the Central and South Atlantic regions.

2.1. Impacts at the individual level

2.1.1. Ocean acidification effects on selected species

Of the taxonomic groups most likely to be directly affected, finfish, mollusks (here, referred to as shellfish), crustaceans, and corals provide the most benefits to fisheries in the Central and South Atlantic regions (Sea Around Us Project http://seaaroundus.org/). Given the negative ocean acidification response seen in many experiments on Eastern oyster, *Crassostrea virginica,* and closely related bivalve mollusks, it seems that artisanal (e.g. yellow clam *Mesodesma mactroides*, Uruguay), small scale/semi-industrial (e.g., queen conch *Strombus gigas*, Caribbean) and bivalve aquaculture fisheries (e.g. *C. virginica*, Brazil) are fisheries that are more likely to be impacted by ocean acidification because they focus on a mollusk species.

Each FAO sub-region in the Central and South Atlantic hosts specific economically important or iconic species that are likely to be especially vulnerable and make up a significant percent of harvest value (Table 1). In FAO area 31, this includes the American cupped oyster, ark clams, and queen conch; in FAO area 34, this includes cuttlefish; in FAO area 41, this could potentially include Argentine shortfin squid, Patagonian squid, Patagonian scallop, and sublittoral bivalve species; in FAO area 47, this includes common squid, arrow squid and cuttlefish (Sea Around Us Project www.seaaroundus.org). This may not be an exhaustive list; additional species may be important for very localized fisheries that are not included here.

2.1.2. Identification of the major threats: $p\mathrm{CO_2}$, Ω

Most ocean acidification studies on individual species have focused primarily on the effects of pH or decreasing calcium carbonate mineral saturation states. Emerging studies suggest that the negative biological consequences of ocean acidification are likely related to energetic consequences (e.g., Navarro *et al.*, 2013), but the exact biochemical mechanism and compound responsible (e.g., CO_3^{2-}, H^+, etc.) for the response are not yet known.

Table 1.

Catch data for potentially ocean acidification-vulnerable species from the Sea Around Us Project (www.seaaroundus.org) for FAO areas 31, 34, 41, 47, covering the Central and South Atlantic.

FAO 31		
Spp	**Country**	**% of total Landed value of that species**
American cupped oyster	Mexico	12.0000
	USA	88.0000
Caribbean spiny lobster	Bahama	39.9315
	Cuba	16.4156
	USA	13.9787
Ark clams	Venezuela	98.0000
	Cuba	2.0000
Blue crab	USA	81.6473
	Mexico	17.7591
	Cuba	0.5483
	Nicaragua	0.0454
Groups	Mexico	46.8524
	USA	38.2338
	Venezuela	9.7884
	Dominican Rp	2.0264
	Bahamas	1.1349
Shrimps	USA	37.7182
	Mexico	34.5184
	Venezuela	12.8547
	Fr Guiana	5.2316
	Nicaragua	2.5955
FAO 34		
Octopuses	Morocco	59.3597
	Mauritania	20.2067
	Senegal	7.6315
	Korea Rep	5.3994
	China Main	2.9161
	Spain	1.7947
	Belize	0.9307
Southern pink shrimp	Nigeria	75.2402
	Senegal	14.1712
	Portugal	4.7708
Cuttlefishes	Morocco	37.5609
	China Main	13.5661

	Spain	9.8517
	Mauritania	8.0809
	Senegal	7.6306
	Italy	7.4921
	Ghana	5.2242
FAO 41		
Argentine shortfin squid	Argentina	38.2947
	Taiwan	18.5608
	Korea Rep	18.4109
	Japan	13.0968
	China Main	4.5593
	Spain	2.6776
	Uruguay	1.7872
	Falkland Is	1.6349
	Ghana	0.1827
	Portugal	0.1517
Patagonian squid	Falkland Is	69.7775
	Spain	8.1688
	France	5.8034
	UK	4.9136
	Australia	3.5514
	St Vincent	2.8238
Patagonian scallop	Argentina	96.0225
	Uruguay	3.9532
	Falkland Is	0.0197
	UK	0.0046
FAO47		
Cape rock lobster	South Africa	87.4203
	Namibia	12.5797

2.1.3. Direct biological responses of the species

Ocean acidification has been shown to alter a variety of life stages, but most often it affects juvenile forms (e.g., larval crabs, bivalves, etc.)(e.g., Long *et al.* 2013; White *et al.* 2013). The processes affected include reproduction, growth, calcification, immunity, olfaction, photosynthesis, etc. (Kroeker *et al.* 2010, 2013; Munday *et al.*, 2012). The population-scale consequences of these individual-based effects are not yet known for most species in most locations. Most importantly for this study, we do not yet know whether ocean acidification will impact market-relevant quantities of specific economically important species, such as meat weight, time to harvestable size, total population numbers, geographic range, etc.

2.1.4. Acclimation and adaptation capacities

The acclimation and adaptation capacities of valuable fisheries in the Central and South Atlantic Oceans are not known. However, upwelling regions on the eastern boundary of this region host high biological productivity and major thriving fin fisheries. These areas routinely experience lower pH and higher CO_2, but the tolerance of finfish living there may have been gained over many generations, and does not necessarily represent an adaptive response that will allow them to tolerate ocean acidification better. At least two hypotheses can be proposed that might explain local species' tolerance of lower-pH, higher-CO_2 conditions: 1) the high level of nutrition provided to the finfish by high biological productivity may provide energy they need to tolerate sub-ideal conditions; or 2) the finfishes' ability to move around may help them control their exposure to adverse conditions. Until more research is completed, it is difficult to propose which changes (e.g., increased variability, change in the mean, etc.) in which factors (whether pCO_2, pH, or CO_3) are biologically relevant for these species, especially because they living in naturally variable or rapidly changing conditions.

2.1.5. Indirect impacts on the species

So far there is no evidence that major open ocean finfish fisheries in this area (e.g. hake, tuna, billfish, sardines, anchovy) will be directly impacted by ocean acidification. The effect of ocean acidification on finfish fisheries is most likely to manifest itself through changes in trophic relationships, such as those related to a decrease in overall food availability and/or the flow of energy among trophic levels (Barry *et al.*, 2011). For example, a main prey species for top fish predators are pelagic squid, which may be affected by ocean acidification (Rosa and Seibel, 2008). A decrease in prey numbers would force predators to find a different food source or decline as well. In some food webs, the demise of one species could benefit others once competition for resources and/or predation pressure decreases, but predicting the outcome and the rate of such a change with high confidence is difficult. Changes in lower trophic levels could impact the abundance of top predators in the food web. Zooplanktivorous fishes may be affected by decrease in abundance of certain species like pteropods or other zooplankton. It is certain that large changes in the relative abundance of species in a given ecosystem as ocean acidification creates "winners" and "losers" will alter the system's role and function (Barry *et al.*, 2011).

Changes or loss in physical habitat structure as a result of ocean acidification could also negatively affect individual species. For example, a reduction in structural complexity of calcium carbonate bioherms and reefs as a result of decreasing calcification and increasing $CaCO_3$ dissolution could increase the competition for space and resources among species. In the Caribbean, coral reefs serve as a critical habitat for many species, but coral health and cover have deteriorated radically in the past several decades owing to a range of factors including overfishing, disease, and warming (Gardner *et al.*, 2003). This decline could intensify as a result of ocean acidification, with negative consequences to those species dependent on the coral reef structure. Similarly, in the eastern Caribbean and off the coast of Brazil, rhodolith beds (i.e., coralline red algae) constitute an important habitat for many species, and may also be at risk from ocean acidification (Amado-Filho *et al.*, 2012). Indeed, several studies have shown that coralline algae may be extremely sensitive to ocean acidification (e.g., Kuffner *et al.*, 2008), potentially leading to significant habitat loss in areas where these organisms serve as ecosystem engineers and builders.

Although carbonate ecosystems are believed to be among the most strongly affected by ocean acidification, changes to non-carbonate dominated ecosystems arising from ocean acidification (positive or negative) or other environmental stressors could also have significant indirect effects on these systems. For example, *Sargassum* seaweed provides a diverse habitat for many species, especially in their early life stages (Laffoley *et al.*, 2011), but the effect of ocean acidification on this habitat is unknown. Nonetheless, if affected at all, this seaweed may benefit from rising CO_2. Regardless of the outcome, both positive and negative indirect effects arising from ocean acidification will likely be difficult to research.

2.2. At population/community level

Fish species that depend highly on habitat provided by coral reefs are also vulnerable via indirect routes. There is a wide array of these reef-associated species, and these typically contribute to smaller-scale fisheries that are nutritionally and economically important. The structural complexity provided by coral reefs is critical in providing a diverse habitat and maintaining high biodiversity. As a result of ocean acidification and other environmental stressors (e.g., overfishing, warming, eutrophication, sedimentation), coral reefs could transition from a state of net accretion to net erosion (Silverman *et al.*, 2009; Andersson and Gledhill, 2013), which would tend to decrease their structural complexity. The result may be a decrease in the abundance and biodiversity of reef-associated species and negative nutritional and economic impacts for the people who depend on them.

For example, the Mesoamerican reef ecosystem is also affected by ocean acidification (Gledhill *et al.* 2008, 2009) and has multiple users and values. They include: (i) commercial fisheries targeting high value gastropods like queen conch (*Strombus gigas*), crustaceans like spiny lobster (*Panulirus argus*) which could be affected by ocean acidification during its long larval stages of 8-10 months, and a diversity of reef dependent fish species like groupers (*Epinephelus spp.*) and snappers (*Lutjanus spp.*); (ii) non-consumptive users like divers who derive satisfaction from observing the reef ecosystem (i.e. eco-tourism); (iii) shoreline residents and users whose interests are partially protected by coral reefs from storm damage caused landfalling hurricanes; (iv) existence values reflected in those who are willing to pay to derive satisfaction by knowing that threatened reefs and reef associated species like the hawksbill turtle (*Eretmochelys imbricata*), and corals in general, are being protected through international organizations, local government institutions, and NGO´s; and (v) option demand values associated to benthic invertebrates which are also rich sources of bioactive compounds with various medical, industrial and commercial applications (Seijo 2007). Because of the above, it is essential to know possible pH reduction consequences on commercially and food security important species (Cooley 2009).

2.3. Consequences in terms of socio-economics

Thus far, there have been no documented ocean acidification-related losses in economically important species in the Central and South Atlantic Oceans. We can therefore only speculate at which species may be affected by analogy with related species, and we can only identify which communities are strongly dependent now. This approach only provides a small hint at the possible impacts of ocean acidification on the region, and no information on economic consequences beyond the early studies already in the literature (Brander *et al.* 2009, Narita *et al.* 2012, Cooley and Doney 2009, Cooley *et al.* 2012).

3. ECONOMIC IMPACTS OF OCEAN ACIDIFICATION

3.1. Current data

The total landed value of fish in Central and South Atlantic is about USD$14.5 billion in 2005 real dollars and contributes to 14% of the global landed value in 2005 (Swartz *et al.* 2012). In this region, many species that contribute strongly to landed values could be affected by ocean acidification (Table 1).

In the Central Western Atlantic, American cupped oyster (*C. virginica*), Penaeus shrimps and Caribbean spiny lobster (*P. argus*) are three of the species with the highest landed value in the 2000s (Figure 8). In Central Eastern Atlantic, the most economically important species are European pilchard (*S. pilchardus*), Bigeye tuna (*Thunnus obesus*) and Madeiran sardinella (*S. maderensis*) (Sumaila *et al.* 2007; Swartz *et al.* 2012) (Figure 9). These species are not only major sources of food for local communities and fishing countries in these regions, but are also economically important as they act as major trade commodities.

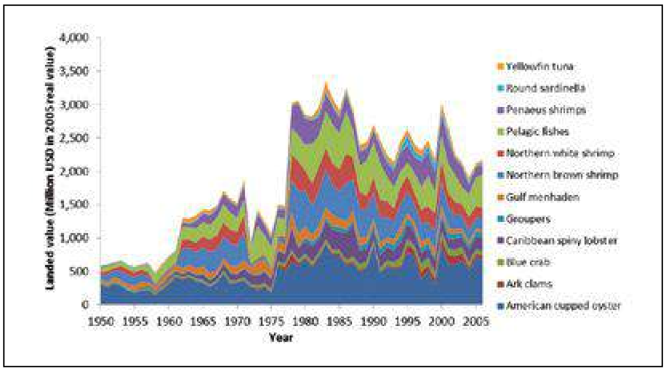

Figure 8:

Historical landed value (in 2005 real value) of top 12 species, which have the highest annual average catches in the 2000s (from 1997 to 2006), in Central Western Atlantic
(Sea Around Us Project).

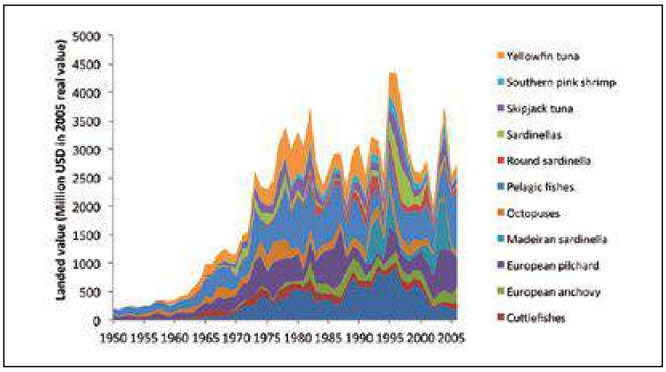

Figure 9:

Historical landed value of 12 species, which have the highest annual average landed value in the 2000s (from 1997 to 2006), in Central Eastern Atlantic
(Sea Around Us Project).

In the South Atlantic, the upwelling systems also support many large and economically important fisheries. In the Southwest Atlantic, Argentine hake and Argentine shortfin squid are the two major exploited species and their landed value contribute to 30% and 20% of the total landed value in this region, respectively (Sumaila *et al.* 2007, Swartz *et al.* 2012) (Figure 10). In Southeast Atlantic, hakes and bigeye tuna are the two most economically important species in this region (Figure 11).

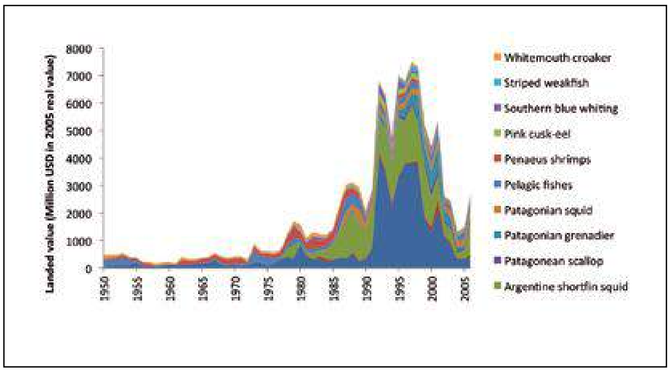

Figure 10:

Historical landed value of 12 species, which have the highest annual average landed value in the 2000s (from 1997 to 2006), in Southwest Atlantic
(Sea Around Us Project).

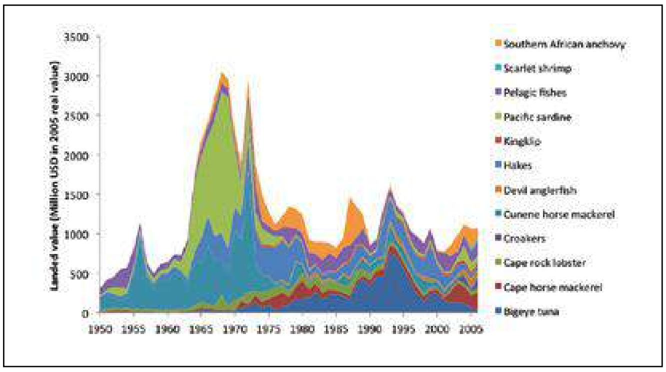

Figure 11:

Historical landed value of 12 species, which have the highest annual average landed value in the 2000s (from 1997 to 2006), in Southeast Atlantic
(Sea Around Us Project).

Most of the countries in the Central and South Atlantic rely on fish and fisheries as major food and income sources. Fish is also the major trade commodity of these countries. For example, Brazil and Mexico are two of the major world's exporters of fish (FAO 2012). FAO (2012) indicates that regional trade in South and Central America continues to be of importance.

Apart from expansion of specific fisheries over time and the introduction of newly exploited species, there have not been marked sudden changes in fishery harvests in South and Central Atlantic Ocean nations (Figures 12-16). Regional trends towards expansion and higher harvests match those observed worldwide.

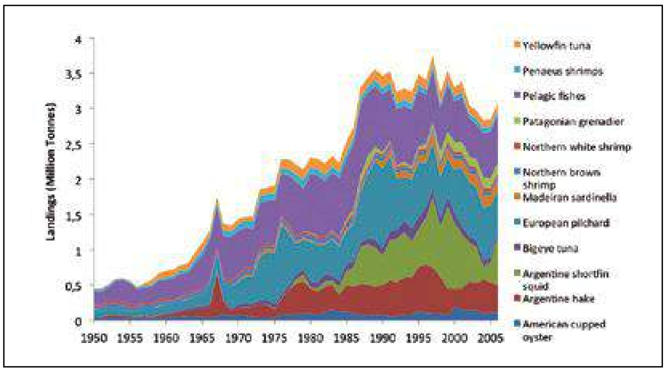

Figure 12:

Landings by economically valuable species in Central and South Atlantic (FAO 31, 34, 41, 47). Historical landings of 12 economically valuable species, which have the highest annual average landed value in the 2000s (from 1997 to 2006), from the Sea Around Us Project (www.seaaroundus.org).

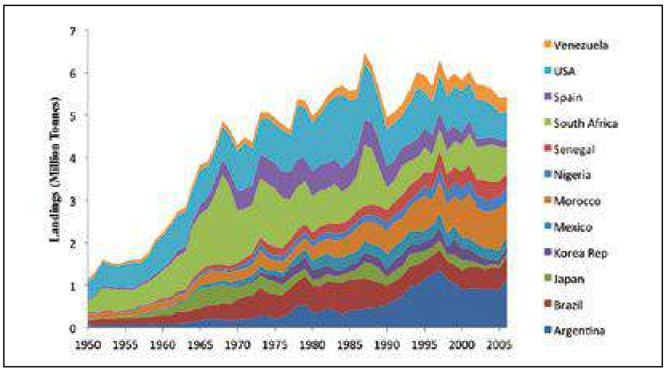

Figure 13:

Landings by countries with high landed values in Central and South Atlantic (FAO 31, 34, 41, 47). Historical landings of 12 countries, which have the highest annual average landed values in the 2000s (from 1997 to 2006), from the Sea Around Us Project (www.seaaroundus.org).

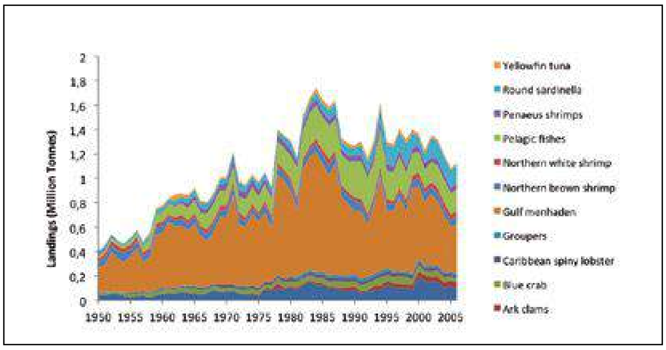

Figure 14:

Landings by economically valuable species in Western Central Atlantic (FAO 31). Historical landings of 12 economically valuable species, which have the highest annual average landed value in the 2000s (from 1997 to 2006), from the Sea Around Us Project (www.seaaroundus.org).

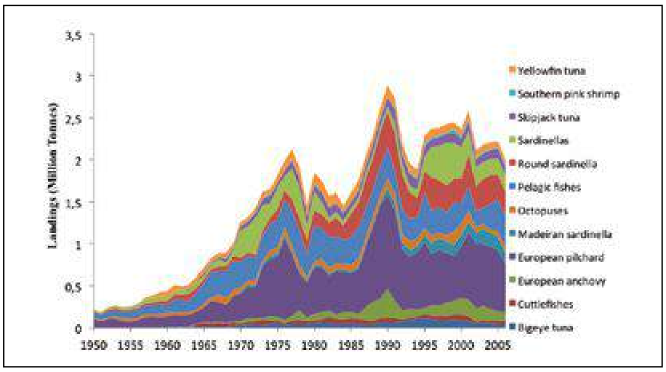

Figure 15:

Landings by economically valuable species in Eastern Central Atlantic (FAO 34). Historical landings of 12 economically valuable species, which have the highest annual average landed value in the 2000s (from 1997 to 2006), from the Sea Around Us Project (www.seaaroundus.org).

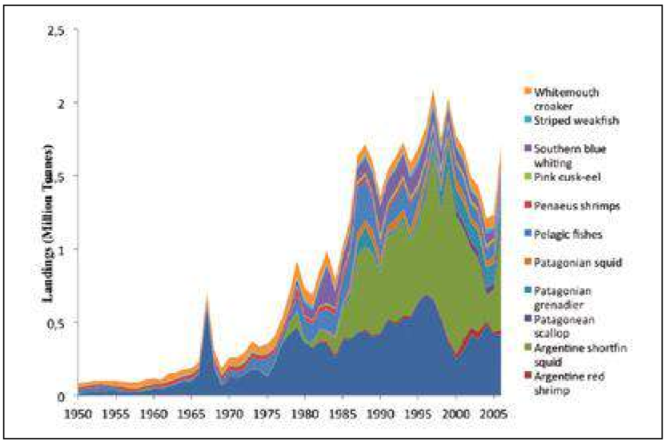

Figure 16:

Landings by economically valuable species in Southwest Atlantic (FAO 41). Historical landings of 12 economically aluable species, which have the highest annual average landed value in the 2000s (from 1997 to 2006), from the Sea Around Us Project (www.seaaroundus.org).

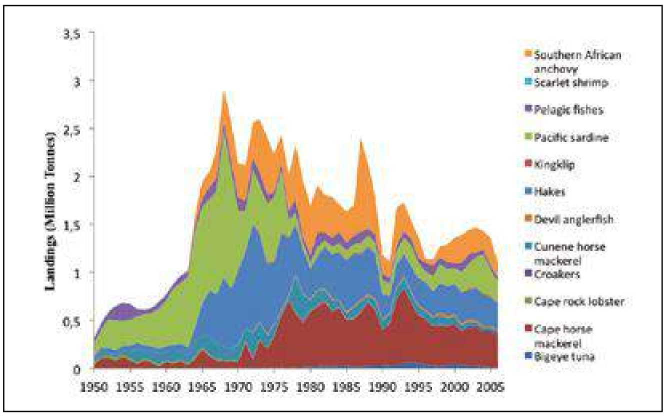

Figure 17:

Landings by economically valuable species in Southwest Atlantic (FAO 41). Historical landings of 12 economically valuable species, which have the highest annual average landed value in the 2000s (from 1997 to 2006), from the Sea Around Us Project (www.seaaroundus.org).

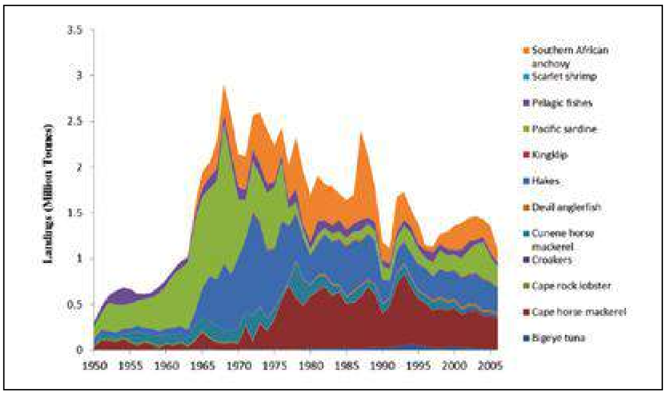

Figure 18:

Landings by economically valuable species in Southeast Atlantic (FAO 47). Historical landings of 12 economically valuable species, which have the highest annual average landed value in the 2000s (from 1997 to 2006), from the Sea Around Us Project (www.seaaroundus.org).

3.2. Role of fisheries in the economy

Commercial fishing brings significant annual revenues for nations bordering the Central and South Atlantic Ocean (Tables 2-3). Many of the most economically important species are finfish and top predators (Tables 4-7), making the links between ocean acidification and large economically important commercial activities difficult to trace since these species have not demonstrated major ocean acidification responses yet.

Table 3:

Countries with the highest total annual landed values (10-year average from 1997 to 2006) in Central and South Atlantic (FAO 31, 34, 41, 47) from the Sea Around Us Project (www.seaaroundus.org)

Country	Landed values (USD million)
Argentina	2,724
USA	1,411
Morocco	918
Spain	798
Brazil	766
Mexico	617
Japan	580
Korea Rep	562
Venezuela	553
Nigeria	547
Senegal	461
South Africa	402

Table 2:

Species with the highest annual average landed values (10-year average from 1997 to 2006) in Central and South Atlantic (FAO 31, 34, 41, 47) from the Sea Around Us Project (www.seaaroundus.org).

Taxon Name	Common Name	Landed values (USD million)
Merluccius hubbsi	Argentine hake	1,560
Marine fishes not identified	Pelagic fishes	1,341
Illex argentinus	Argentine shortfin squid	1,008
Thunnus obesus	Bigeye tuna	595
Crassostrea virginica	American cupped oyster	584
Sardina pilchardus	European pilchard	469
Macruronus magellanicus	Patagonian grenadier	422
Penaeus	Penaeus shrimps	360
Thunnus albacares	Yellowfin tuna	311
Sardinella maderensis	Madeiran sardinella	272
Farfantepenaeus aztecus	Northern brown shrimp	236
Litopenaeus setiferus	Northern white shrimp	216

Table 4:

Species with the highest annual average landed value (10-year average from 1997 to 2006) in Western Central Atlantic (FAO 31) from the Sea Around Us Project (www.seaaroundus.org)

Taxon Name	Common Name	Landed values (USD million)
Crassostrea virginica	American cupped oyster	584
Marine fishes not identified	Pelagic fishes	381
Penaeus	Penaeus shrimps	267
Farfantepenaeus aztecus	Northern brown shrimp	236
Litopenaeus setiferus	Northern white shrimp	216
Panulirus argus	Caribbean spiny lobster	175
Arca	Ark clams	96
Callinectes sapidus	Blue crab	91
Epinephelus	Groupers	74
Brevoortia patronus	Gulf menhaden	71
Sardinella aurita	Round sardinella	67
Thunnus albacares	Yellowfin tuna	62

Table 5:

Species with the highest annual average landed value (10-year average from 1997 to 2006) in Eastern Central Atlantic (FAO 34) from the Sea Around Us Project
(www.seaaroundus.org)

Taxon Name	Common Name	Landed values (USD million)
Marine fishes not identified	Pelagic fishes	578
Sardina pilchardus	European pilchard	469
Thunnus obesus	Bigeye tuna	364
Sardinella maderensis	Madeiran sardinella	272
Thunnus albacares	Yellowfin tuna	215
Sardinella	Sardinellas	181
Katsuwonus pelamis	Skipjack tuna	180
Engraulis encrasicolus	European anchovy	167
Octopoda	Octopuses	120
Sardinella aurita	Round sardinella	117
Farfantepenaeus notialis	Southern pink shrimp	110
Sepiidae	Cuttlefishes	105

Table 6: Species with the highest annual average landed value (10-year average from 1997 to 2006) in Southwest Atlantic (FAO 41) from the Sea Around Us Project
(www.seaaroundus.org)

Taxon Name	Common Name	Landed values (USD million)
Merluccius hubbsi	Argentine hake	1,560
Illex argentinus	Argentine shortfin squid	1,008
Macruronus magellanicus	Patagonian grenadier	422
Marine fishes not identified	Pelagic fishes	226
Loligo gahi	Patagonian squid	216
Zygochlamys patagonica	Patagonian scallop	135
Pleoticus muelleri	Argentine red shrimp	123
Genypterus blacodes	Pink cusk-eel	106
Micromesistius australis	Southern blue whiting	71
Penaeus	Penaeus shrimps	68
Cynoscion striatus	Striped weakfish	59
Micropogonias furnieri	Whitemouth croaker	48

Table 7:

Species with the highest annual average landed value (10-year average from 1997 to 2006) in Southest Atlantic (FAO 47) from the Sea Around Us Project
(www.seaaroundus.org)

Taxon Name	Common Name	Landed values (USD million)
Merluccius	Hakes	157
Marine fishes not identified	Pelagic fishes	156
Thunnus obesus	Bigeye tuna	150
Trachurus capensis	Cape horse mackerel	126
Engraulis capensis	Southern African anchovy	91
Trachurus trecae	Cunene horse mackerel	64
Sardinops sagax	Pacific sardine	62
Lophius vomerinus	Devil anglerfish	43
Plesiopenaeus edwardsianus	Scarlet shrimp	42
Genypterus capensis	Kingklip	35
Jasus lalandii	Cape rock lobster	35
Pseudotolithus	Croakers	32

Case study: West African nations

The east side of the Central Atlantic region is bounded by West African countries. West Africa is highly dependent on fish and fisheries as source of food and income. The average annual per capita food fish consumption of West Africa is 14.6 kg per capita, with Senegal having the highest consumption (27.8 kg per capita) in the region in the early 2000s (averages from 1999–2003) (FAO, 2011). Although the annual per capita consumption of fish in West Africa is not as high as that in other regions and also lower than the global average annual per capita consumption (15.9 kg per capita from 1999 to 2003, FAO, 2011), West Africans generally eat less animal protein than other people in more developed countries, but they consume more fish. Thus, comparing fish dependence in West Africa with other regions is more instructive than comparing the absolute figures of fish consumption per capita. Fish also acts as an important source of essential micronutrients such as iron, iodine, zinc, calcium, vitamin A and vitamin B that are not found in other staples such as rice, maize and cassava (Roos *et al.,* 2007, Kawarazuka, 2010). Due to the decline in the performance of agriculture and other natural resource sectors, the main source of cheap animal protein for many West African states is from coastal and offshore fisheries, and fish harvested from capture fisheries and aquaculture contributes as much as 50% of animal protein consumed in these countries (FAO, 2009, Smith *et al.* 2010). Countries in West Africa also rely on fish and fisheries as a source of income, providing jobs for 7 million West and Central Africans (FAO, 2006). The value-added from fisheries allows people to purchase high calorie staples such as rice and wheat, and other nutritious food such as vegetables and meat.

Although marine fish and invertebrates exported from West Africa are worth only US$ 600 million annually (FAO, 2007) and contribute only about 2% to the total export value from West

Africa countries, the fisheries sector in the region plays an important role in the local economy of certain West African countries; e.g., Mauritania and Senegal are net exporters of fish. However, Smith *et al.* (2010) revealed that the low level of exports from West Africa relative to other regions reflects access agreements between West African countries and countries in Europe and Asia. The landings under these access agreements are not considered to be African exports, because the value of license agreement fees is counted in another category. Furthermore, the fisheries sector, particularly the artisanal sector, is a major source of employment and income for unskilled young men and women of coastal communities through direct and ancillary activities (FAO, 2006).

Current status and problems of fisheries in West Africa

Fisheries resources are highly productive along the continental shelf of West Africa. The high productivity is supported by the upwelling resulting from the Canary Current and Guinea Current along the coast of Western Africa. Currently, fish stocks in West African waters are already overexploited, driven to a large extent by the dominance of foreign distant water fleets in the Exclusive Economic Zones (EEZs) of the West African countries (Alder and Sumaila, 2004; Atta-Mills *et al.,* 2004). Before the enactment of the United Nations Convention on the Law of the Sea (UNCLOS) in the 1980s, fishing vessels from the European Union (EU) fished freely in African waters. Later with UNCLOS, the EU officially negotiated and signed bilateral fishing agreements with Western African countries (Alder and Sumaila, 2004). The main EU countries that fished in West Africa were France, Spain and Portugal; the former Soviet Union and China were also strongly involved. Moreover, some EU countries found an indirect way to fish in West African waters through joint ventures with local businesses. The total number of years foreign countries signed agreements with Western Africa countries for fishing access added together for each decade have increased significantly since they first started in the 1960s (Alder and Sumaila, 2004). The negotiations and agreements are usually made at political levels with almost no involvement of local scientific or community inputs from West Africa countries. Simultaneously, there was a strong demand for fisheries resources as source of food, income and livelihoods for coastal Western African communities. As a result, fisheries resources in West African waters are heavily exploited both by local fleets, which are mainly small scale artisanal, and foreign vessels starting in the 1960s.

This pressure has caused the decline of fish stocks; however, the demand for fish keeps increasing, as a result, fishers are using more and more sophisticated, sometimes destructive methods and illegal means, to fish (Pauly, 1990; McClanahan *et al.,* 2005). High-technology fishing techniques with the potential of finding the last remaining fish, which do not leave part of the stock to reproduce, are being used (Ovetz, 2007). Some fishing gears are simply destructive to the ecosystem, such as bottom trawling by the industrial fishery, which sweeps the ocean floor and clears everything in its way, or dynamite fishing by small scale fisheries such as those near the coast of Dakar (Campredon and Cuq, 2001) and in Moree, Ghana, before dynamite fishing was banned through co-management (Overå, 2001). In addition, artisanal fishers, for example, in Ghana, use very small mesh sizes, which catch very small fish before they become sexually mature. Trawlers sometimes operate close to the shore, destroying coastal habitats and the gear of artisanal fishers (Overå, 2001). A global assessment of illegal fishing found West Africa to be an area of high risk with an estimated illegal catch of 40% above the reported catch (Agnew *et al.,* 2009). Together with other problems such as discard of by-catch (Kelleher, 2005) and the trash fish trade (Nunoo *et al.,* 2009), all these stresses in the region's fisheries increase the number of people at risk of facing hunger (Brown and Crawford, 2008; Shah *et al.,* 2008). Therefore, the impacts of climate change (Lam *et al.,* 2012) and ocean acidification may add further stresses to the fisheries, economic and food security issue to this region.

3.3. Forecast (or scenarios)

Until now, the potential impacts of ocean acidification on marine species and their subsequent economic impacts in Central and South Atlantic are still not well-studied. However, some modeling studies have been already conducted in other regions. Although one global model (e.g., Cheung *et al.,* 2010) suggest that climate change may lead to increases in the potential fisheries catch in higher-latitude regions, follow-up studies with a model that accounts for hypothesized physiological effects of ocean acidification suggest that there may be a substantial reduction in potential fisheries catch in more acidic water in the North Atlantic (Cheung *et al.,* 2011). These potential changes are expected to have direct implications for fisheries and economies through changes in the quantity, quality and predictability of catches (Sumaila *et al.,* 2011).

Studies have shown that ocean acidification reduces coral calcification and favors invasive non-native algal species (Hoegh-Guldberg *et al.*,2007) and negatively affected shellfish and fish (e.g., Kroeker *et al.,* 2010, 2013). Hence, the diversity of coral ecosystems is likely to decrease. In one study by Brander *et al.* (2009), the loss in coral reef area was projected to range from 16% to 27% under different scenarios and the annual economic loss was estimated to be $870 billion in the A1 scenario in 2100. Cooley & Doney *et al.* (2009) also estimated that a substantial loss in revenue, job losses and indirect economic costs may occur in the United States because of ocean acidification, which may have serious impact on marine habitats and hence mollusk fisheries. As some countries depend heavily on mollusks for food and economics, countries with high vulnerability to ocean acidification were also identified in Cooley et al (2012). Although there is still no detailed study on the economic impact of ocean acidification on global fisheries, it seems reasonable to assume that the direct impacts associated with ocean acidification might eventually impose costs on the order of 10% of marine fishery production, perhaps something on the order of $10 billion/year (Kite-Powell, 2009). Moreover, given the strong probability that ocean acidification will act hardest on near-shore and smaller scale fisheries in this region, it has the potential to worsen food distribution inequality that already exists and remove an important source of revenue to coastal communities in Central and South Atlantic.

4. CASE STUDIES

Several iconic species and environments were identified that, if negatively impacted by ocean acidification, would immediately have socioeconomic effects because they are important to a range of human communities and span the full range of environments in the Central and South Atlantic Ocean. These might include: 1) Queen conch (*S. gigas*) in the Caribbean, which is commercially and nutritionally important, and governed over multiple boundaries through large marine ecosystem boundaries. 2) The Mesoamerican barrier reef, which has been the subject of a great deal of research. 3) Oysters, including aquaculture in Brazil and wild harvest in the United States. 4) Yellow clams (*M. mactroides*) along the South American coastline, which are fished in an artisanal scale fishery and are important to human communities for subsistence and identity. However, ocean acidification responses and effects on human communities for these case studies have not been determined yet. We can only infer possible responses based on those of closely related species (c.f. Kroeker *et al.*, 2013), underscoring the need for more research on these regionally critical species.

Of these species, the ocean acidification response of the Eastern oyster (*Crassostrea virginica*) has been best studied. Chapman *et al.* (2011) reported that the two environmental factors that dominate physiological effects for eastern oyster (*Crassostrea virginica*) are temperature and pH, which interact in a dynamic and nonlinear fashion to impact gene expression. Transcriptomic data obtained in their study provide insights into the mechanisms of physiological responses to temperature and pH in oysters that are consistent with the known effects of these factors on physiological functions of ectotherms and indicate important linkages between transcriptomics and physiological outcomes. Furthermore, Talmage and Gobler (2011) report negative effects on survival and growth (both speed and shell thickness) of *C. virginica* larvae.

5. POLICY RECOMMENDATIONS

It is widely acknowledged that the most important policy action that can be taken to mitigate ocean acidification is cutting atmospheric carbon dioxide levels, most effectively by addressing CO_2 emissions rates. Until that occurs, more regional policies will need to be implemented to encourage local mitigation or adaptation efforts responding to ocean acidification.

In the Central and Southern Atlantic Ocean, both small- and large-scale fisheries depend on species that could be harmed by ocean acidification. Marine management policies designed to regulate the location and quantities of marine harvests, or preserve vulnerable species, are most likely the first response that communities will take in the face of ocean acidification (e.g., Washington State Blue Ribbon Panel Report, 2012). If ocean acidification and temperature rise result in range shifts of vulnerable yet economically important species (Cheung *et al.* 2010), small-scale fishers will require local management strategies that are flexible enough to allow them to target a changing variety of species using different gear types. It is more likely that small-scale fishers will be able to change their fishing methods than their locations or ranges of fishing. Therefore, helping subsidize changing gear, retraining local fishers for other occupations, or helping identify and cultivate nutritional alternatives will likely be necessary for many local jurisdictions in the Central and Southern Atlantic, given the relatively low regional income and social resilience in many bordering nations. Large-scale fishers, on the other hand, may need policies that are geographically flexible (e.g. larger fishing areas) that allow them to go farther afield for the same species as long as it is economically feasible.

Lack of consideration for the potential future consequences of ocean acidification in this region by policymakers could result in policies that are appropriate at present but do not build a resiliency “cushion” into ecosystems that will prepare them to withstand chronic temperature and acidification stresses coming in the next several decades. For example, policies that permit destructive use of coral reefs could decrease coral habitat and structure enough that the system is closer to a “tipping point” (Hoegh-Guldberg *et al.* 2007) and more likely to become irrevocably damaged by acidification in the near future. Eliminating dynamite fishing, as several nations already have, is a good example of one possible way to build additional resiliency into marine ecosystems by not wasting extra natural resources.

5.1. Survey of policy mechanisms

Because the Central and South Atlantic has not experienced demonstrated negative consequences from ocean acidification yet, it is difficult to predict what policies or governance approaches will be most appropriate. However, there are some general principles that have been successful elsewhere that will likely be useful here as well. Close coordination among local, regional, and national authorities as well as user groups and researchers has been demonstrated to yield quick, effective responses to ocean acidification events elsewhere (Washington State Blue Ribbon Panel, 2012). Involving end-users in decision-making and governance leads to more effective outcomes. Support for social systems is needed to facilitate shifts within the human community that may become necessary, such as livelihood diversification and education, due to changes in marine benefits from acidification or other environmental changes. All of these principles can be more challenging in nations like those bordering the Central and South Atlantic, which are less wealthy and less well developed, and which depend more heavily on local fisheries for animal protein and family income.

6. Suggestions for further research needed to fill the gap between natural sciences and economics

Several general knowledge gaps exist in the natural science that could provide economically relevant information. In most of the Central and South Atlantic (especially FAO regions 31, 41, and 47), commercial harvests of crustaceans (lobster, crabs, shrimp) provide high commercial revenue, yet more research is needed to verify whether or not they are vulnerable to ocean acidification. Furthermore, an understanding of baseline ocean chemistry and community conditions is needed, especially in coastal zones where more vulnerable species (like bivalve mollusks) are harvested. This understanding will allow later assessments of change in regional ecosystems relative to today’s baseline. Future global change studies should be integrated to address the effects of multiple stressors including ocean acidification, change in surface temperature, sea-ice extent, and decrease in dissolved oxygen concentrations (and the increase oxygen minimum zones (hypoxia)) on marine ecosystems, rather than individual species. Multiple stressor research is important at all scales, from large marine ecosystems (LMEs) to small-scale fisheries. Most economically important for the Central and South Atlantic region are studies determining how or whether ocean acidification will affect the harvest of significant quantities of top predatory finfish or iconic local species.

From a policy standpoint, several opportunities exist at local to basin scales. A regional fisheries management organization in FAO area 41 is needed to address ocean acidification as well as other regional issues in fisheries planning, especially for management of squid and other transboundary species. In smaller-scale fisheries, local community-focused adaptation policies are likely to be most effective for responding to changing conditions caused by ocean acidification there. However, these are most effective for overall management of small-scale fisheries, and developing these policies does not represent a major shift; rather, it represents a slight expansion of the breadth of issues being presently considered and the timescale of their action.

Depending on how ocean acidification manifests in the Central and South Atlantic Ocean, it has the potential to worsen social inequalities that already exist. The strong economic importance of finfish fisheries in the central and south Atlantic Ocean that will likely not be directly affected by ocean acidification could partially obscure the large potential for certain communities and sub-regions to be affected by ocean acidification. Many commercially and culturally important mollusk species and reef-habitat-dependent fish species may be affected by ocean acidification, given the negative response of closely related mollusk and coral species investigated in other studies. These species are usually harvested by smaller scale and artisanal fishers, in contrast to the large industrialized finfish fisheries in the Central and South Atlantic. The dissimilarity of these two fishery categories and their responses points to the need for policy and adaptation research that address different scales: industrial and large scale vs. artisanal and small scale. It may be worthwhile to frame this work in these two major categories to organize impacts and responses.

The possible effect on fisheries targeting commercially important and or food security species call for answering to essential questions: (i) How could we incorporate ocean acidification effects in the bio-economics of mollusks and crustacean fisheries?, and (ii) How can we deal with new uncertainties inherent to the effects of ocean acidification on calcifying species and coral reef ecosystems in the absence of probabilities of occurrence of possible states of nature (i.e. possible ocean pH changes)? In seeking to address these questions and put answers into action, we must keep in mind realistic use patterns and human behavior. For example, it is important to rebuild sustainable fishing and resilient populations, but to do so in the most suitable places, for example, shallower and more productive marine ecosystems. Adaptive responses to these changes should include 1. technological (e.g. modification of fishing gear), 2. behavioral (e.g. choice of fishing grounds and/or target species), 3. managerial (e.g. human resources management) and 4. policy (e.g. fisheries management) components to be most effective.

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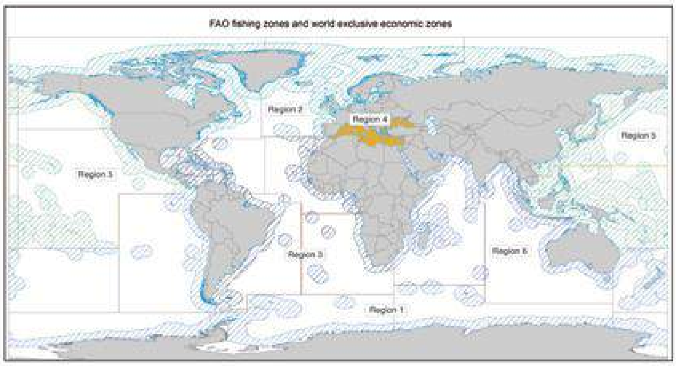
Mediterranean and the Black Seas region

(FAO 37)



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See map in Annex 1, p. 133.

EXECUTIVE SUMMARY

The Mediterranean and Black Seas – that represents 1% of worldwide ocean area – are considered as important hotspots of biodiversity, hosting up to 10% of the world's species. At the same time, these regional seas constitute a worldwide market for fisheries and aquaculture activities. In fact, both sectors represent 1% of the world landings and 2% the value of market transactions. Fisheries are mainly based on small pelagic captures, aquaculture focused at 90% on bivalves, e.g. *Mytilus galloprovincalis* and *Crassostrea gigas.* Whereas the fisheries catches remain quite stable since 90's, the aquaculture production is constantly increasing in the two past decades. In the Mediterranean, these economic activities are responsible for the creation of 380,000 jobs (250,000 and 130,000 in fisheries and aquaculture, respectively) and 210,000 indirect employments.

In this context, ocean acidification becomes an issue of particular significance for both conservation policy design as well as for coastal management of fisheries and aquaculture economic activities. Clearly, the ocean acidification is known to affect the shell calcification of molluscs. Furthermore, increasing temperatures and heat wave frequency in this area is already killing many Mediterranean organisms or pushing them by the edge of their thermal limits. Ocean acidification is expected to worsen the effects of ocean warming on mussels, other molluscs and corals. The early life stages of bivalve are the most vulnerable to combined increasing temperature and CO_2. Recruitment and seed production would be thus the main bottleneck for shellfish aquaculture in Med Sea in the future. Fisheries and fish aquaculture might be also affected through indirect effect of ocean acidification on the environment, but ecological mechanisms are less known. While individual fish seems able to cope with seawater CO_2 increase, the degradation of essential habitats such as coralligenous, vermetid reefs and coral banks, used as nursery grounds by marine organisms might affect fish stocks. Inversely, increasing CO_2 levels benefit or do not affect certain organisms such as harmful algal bloom, and non-calcified anthozoans, including jellyfish which can sting people and kill farmed fish.

The distribution of the magnitudes of the socio-economic impacts of ocean acidification in Med Sea will reflect the differences of the country's basin economies (e.g. north *vs* south gradient) as well the country's livelihoods dependence on fish protein. In Black Sea, artisanal fishers have been adversely affected by declining fish populations due to overfishing. Even if the contribution of captures fisheries and aquaculture production to the national GDP is less important that tourism in the Mediterranean, some countries more exposed to the impacts of ocean acidification since their economies are characterized by a significant fisheries and aquaculture sectors (e.g. total production of shellfish in Med & Black Seas is more than 180,000 tons represented by the Mediterranean mussel, the Japanese carpet shell and the Pacific cupped oyster. Italy, Greece, France and Spain are the main producers. Marine and brackish fish production is more than one million of tonnes, mainly from Egypt, Greece, Turkey, Italy and Spain).

1. THE SPECIFICITIES OF THE REGION

1.1. Geography

The Mediterranean Sea is a remnant of the east-west oriented Tethys Ocean, which 200 million years ago (Ma) separated the two super-continents: Laurasia in the North and Gondwana in the South. Connection between the Mediterranean Sea and the Indian Ocean permanently ceased 12-13 Ma, and since then the Mediterranean has been a semi-enclosed sea. During the Late Miocene (5.9- 5.3 Ma), the connection between the Mediterranean and the Atlantic Ocean was interrupted on several occasions (Garcia-Castellanos and Villaseñor, 2011). This caused a drying of the Mediterranean Sea that was successively repopulated by species of Atlantic origin. Today the Mediterranean Sea has restricted exchange of seawater with the Atlantic Ocean via the Strait of Gibraltar in the west and the Black Sea in the east and even to a lesser extent with the Red Sea via the man-made Suez Canal (Fig. 1) The Mediterranean Sea therefore experiences a variety of conditions that allow co-occurrence of cold, temperate and sub-tropical biota.

Figure 1:

Map of the Mediterranean and Black Sea showing their connectivity with each other, the Atlantic Ocean via the Strait of Gibraltar and the Red Sea via the Suez Canal. Borders and the name of the countries are given.
Background map is a screenshot from NASA World Wind.

The Black Sea is ultimately connected to the Atlantic Ocean via the Mediterranean Sea by the Bosphorus Strait (which connects it to the Sea of Marmara) and the Strait of the Dardanelles (which connects the Sea of Marmara to the Aegean Sea region of the Mediterranean Sea (Fig.1). These waters separate Eastern Europe and Western Asia. The Black Sea is also connected to the Sea of Azov by the Strait of Kerch.

Mediterranean water flows into the Black Sea as part of a two-way hydrological exchange. The Black Sea outflow is cooler and less saline (due to high riverine input), and floats over the warm, more saline Mediterranean inflow – as a result of differences in density caused by differences in salinity – leading to a significant anoxic layer well below the surface waters. The Black Sea receives river water from large Eurasian fluvial systems to the north of the Sea, of which the Don, Dnieper and Danube are the most significant. In the past, the water level in the Black Sea has varied significantly and at times isolating it from the Mediterranean Sea so that it became a lake, operating independently of the global ocean system.

1.2. Biological and chemistry characteristics

The Mediterranean Sea can be considered as a small-scale ocean with oligo- or ultraoligo- trophic waters with a high environmental variability and steep physico-chemical gradients within a relatively restricted region: salinity, temperature, alkalinity and stratification all tend to increase eastwards. The general oligotrophy of Mediterranean waters contrasts with several coastal settings affected locally by human-induced eutrophication, such as the Adriatic Sea. Due to the important freshwater releases from the Danube River, the Black Sea is defined by low salinity (around 18 ‰) and high nutrient concentrations that often lead to eutrophication and stratification of water masses.

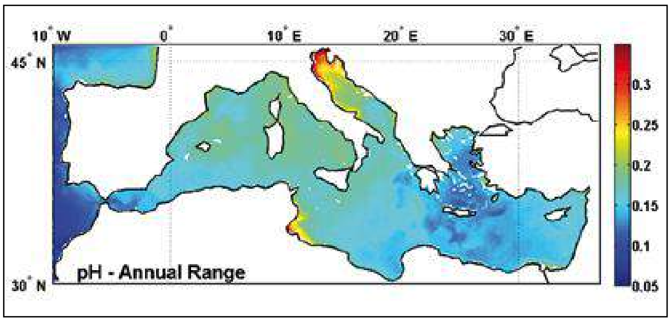

Figure 2:

Spatial distribution of pH seasonal ranges driven by physical processes only (from the high-resolution CMCC model), Lovato T, Vichi M. *et al.,* in prep.

Mediterranean seawater is characterized by a general eastward pattern of increasing sea surface water temperature (SST), salinity (S), oxygen concentration, total carbon (CT) and total alkalinity (TA) (from ~2450 to ~2700 μmol kg^{-1}). Seasonal pH ranges can be very large (Figure 2) particularly in the relatively shallow North Adriatic waters experiencing dramatic temperature anomalies between winter and summer. The SST, S, TA patterns are mainly explained by evaporation coupled with high freshwater alkaline inputs into coastal areas (Schneider *et al.*, 2007; Hassoun *et al.*, subm.) The rate and magnitude of pH decrease due to increased uptake of anthropogenic CO_2 (ΔpH) in the Mediterranean Sea was unknown due to the lack of continuous carbonate chemistry data. Recently Yao *et al.* (subm.) utilized data from the Dyfamed long-time-series (central part of the Ligurian Sea) to estimate the level of acidification in the northwestern Mediterranean Sea. From this study, it was determined that the penetration of anthropogenic CO_2 (C_{ANT}) into the surface water increased C_T by a rate of 4.32 μmol.kg^{-1} per year, which corresponds to a ΔpH of approximately -0.04 pH unit over a period of only 19 years (~-0.0021 yr-1). The results also show that anthropogenic CO_2 adsorption was the key factor controlling the long-term trend of ocean acidification in this Mediterranean site, accounting for 75%, followed by water temperature (31 %), while biological activities favored only a slight decrease in pH (6%). The concentration of estimated anthropogenic carbon is high in the entire Mediterranean due to the high total alkalinity that allows the absorption of relatively more anthropogenic carbon than the open ocean (CIESM, 2008; Touratier and Goyet *et al.*, 2009; Schneider *et al.*, 2007). The Mediterranean Sea stores a large amount of CANT, particularly in the Western Basin (C_{ANT} > 48 *µ*mol kg-1 in the South western Basin and > 21 *µ*mol kg-1 in the North western). This could be explained by thermodynamics: the low Revelle factor, due to warm and high total alkalinity waters, facilitates the absorption of atmospheric CO_2. Then, the vigorous overturning circulation transfers this absorbed CO_2 at depths. In agreement with the earlier works of Aït-Ameur and Goyet (2006), Touratier and Goyet, 2009 and Schneider *et al.*, 2010, these results show that the Mediterranean Sea acts as a source of total inorganic carbon to the Atlantic Ocean, indicating that C_{ANT} is efficiently transferred from the atmosphere to the Mediterranean Sea.

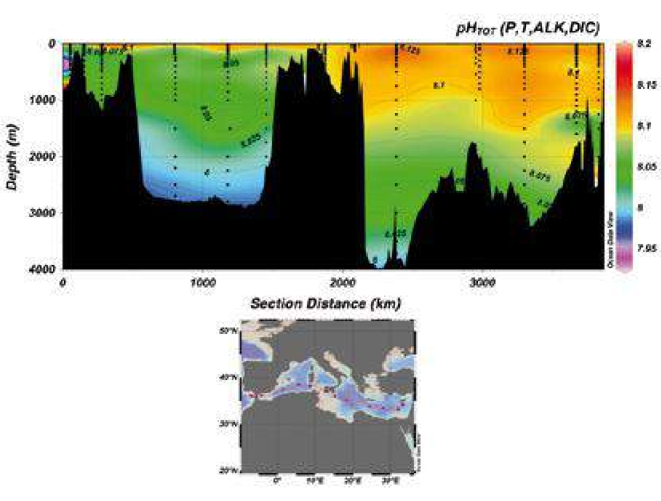

Figure 3:

Distributions of pH estimated from total carbon (CT) and total alkalinity (TA) measurements, during the 2013 MedSeA research cruise (Hassoun *et al.,* subm.).

During an oceanographic cruise by the European project on Mediterranean Sea Acidification in a changing climate (MedSeA) project in May - June 2013 onboard the Spanish R/V Angeles Alvariño and covering the entire Mediterranean, samples were collected to characterize the CO_2 system and several biological parameters. The pH distribution from the first cruise transect is presented in Figure 3.

Limited seawater carbonate chemistry data are available for the Black Sea. The most extensive carbonate system studies to date were published in Goyet *et al.*, 1991 and Hiscock and Millero, 2006. An important feature of the Black Sea water chemistry is the extended anoxia with nearly 87% of the waters being anoxic and containing high levels of sulfide (Hiscock and Millero, 2006). Due to the low salinity and high total alkalinity of river waters entering the Black Sea, the seawater TA in the oxic surface waters (~3500 µmol kg^{-1}) is higher than typical oceanic values (Dyrssen, 1985). In contrast with the Mediterranean Sea, the saturation coefficients of both calcite and aragonite Ω_{Cal} and Ω_{Arg} show under saturation at depth. The value of Ω_{Cal} is less than 1 in anoxic waters below seawater density σ_t ~16.9 (~400 m) and Ω_{Arg} is less than 1 in anoxic waters below σ_t ~14.8 (~60 m) Hiscock and Millero, 2006. In addition to the complex carbonate chemistry, an intensive eutrophication of the ecosystem caused by anthropogenic perturbations in both the Black Sea waters and the drainage basins of its major supplying rivers can greatly influence surface water coastal acidification.

The Mediterranean Sea is considered as one of the 25 hotspots of global biodiversity, hosting 7% of the world's species (4-18% according to the considered phylum) living in 0.82% of the ocean area and 0.28% of the ocean volume. Species diversity in the Black Sea is 3.5 times poorer than in the Mediterranean Sea. This difference reflects the considerably lower salinity in the Black Sea and large volume of anoxic waters. Black Sea biodiversity is also characterized by the presence of many taxa of boreal origin. Some of these species have been recently introduced from the Baltic Sea through the fluvial transport.

1.3. Main stressors

Global, regional and local stressors are occurring in both seas at the same time and may have synergistic impacts (Gambaiani *et al.,* 2009). These human-induced stressors include warming, acidification, deoxygenation, eutrophication, desalination, overfishing, pollution (Sacchi, 2008; GFCM, 2011) and habitat destruction (Claudet & Fraschetti, 2010; Coll *et al.*, 2010; Durrieu de Madron *et al.*, 2011) and are already challenging marine organisms, ecosystems and the ecosystem goods and services that these seas are providing human society.

The ways in which these multiple stressors interact in the Mediterranean and Black Sea may provide useful insights for potential impacts elsewhere as the region is well monitored for many physical, biological, chemical and sociological parameters. In a recent empirical analysis of the human stressors applied to this region, climatic drivers (ocean warming and acidification) have been highlighted as the most impacting followed by overfishing, the nutrient-release hypoxia, invasive species, and pollution (Micheli *et al*., 2013).

Ocean warming

As occurs in many other ocean regions, the Mediterranean and Black Seas are experiencing warming with a rise of the mean maximum summer seawater temperature of around 1°C during the last three decade (Marbà & Duarte, 2010) as well as an increase of heat wave occurrence (Coma *et al.*, 2009). This increase in seawater temperature is altering the biogeographic boundaries and leading to a progressive 'meridionalization' of Mediterranean marine biota (CIESM, 2008a). Changes include an increase in abundance of eurythermal (*i.e.* wide thermal range tolerant) species and a decrease in cold stenothermal (*i.e.* narrow thermal range tolerant) species as well as northward species shifts and increase in mass mortalities during unusually hot summers (Coll *et al.*, 2010). For example, the warm-water fish such as the ornette wrasse (*Thalassoma pavo*), the barracuda (*Sphyraena* spp.), the groupers (*Epinephelus* spp.), the Mediterranean parrotfish (*Sparisoma cretense*) and the round sardinella (*Sardinella aurita*) have spread northwestwards. Certain cold water species have been replaced, for example the distribution of the cave-dwelling mysid (*Hemimysis speluncola*) has contracted and been replaced by the mysid (*H. margalefi*), a warm water species that was previously unknown in the northwestern Mediterranean Sea (Chevaldonné & Lejeusne, 2003). Beyond these distribution shifts of indigenous species, alien warm water species of algae, invertebrates and fish are increasing their geographical ranges (Bianchi, 2007; Lejeusne *et al.*, 2010, CIESM, 2008b). These invasive tropical fauna and flora now form a significant portion of the biota in the southern Mediterranean and some out-compete native species (Lasram & Mouillot, 2009).

Seawater warming challenges the metabolism and the physiology of organisms such as the mussel *Mytilus galloprovincialis* which are being pushed towards their upper thermal limit (Anestie *et al.*, 2007) during summer and autumn periods when seawater temperature reaches up to 26°C. Higher temperatures and increased numbers of heat wave events are likely to cause mass mortalities of adult populations of the endemic seagrass *Posidonia oceanica* (Diaz-Almela *et al.*, 2009), invertebrates (Coma *et al.*, 2009), and habitat-forming sponges and corals (Garrabou *et al.*, 2009) as well as juveniles of a wide range of metazoan organisms (Byrne, 2011).

Warming of surface waters increases the evaporation rate and seawater density, and may strengthen stratification of the water column and weaken mixing of surface and deeper waters. This will further restrict nutrient availability in ultraoligotrophic zones depleting food availability for commercial fish populations (Kletou & Hall-Spencer, 2012). In addition, increasing temperatures may also contribute to higher frequencies of disease outbreaks as warm-water microbial pathogens are expected to spread (Martin *et al.,* 2002, Danovaro *et al.,* 2009).

The fluvial systems draining Eurasia and central Europe introduce large volumes of sediment and dissolved nutrients into the Black Sea, but distribution of these nutrients is controlled by the degree of physiochemical stratification. During winter, strong winds promote convective overturning and upwelling of nutrients, while high summer temperatures result in a marked vertical stratification and a warm, shallow mixed layer. However, warmer winters may be characterized by a limited vertical mixing of waters and weaker upwelling velocity causing stronger stratification and less nutrients in photic waters for primary productivity (Oguz *et al.*, 2003).

Habitat loss

Habitat destruction is considered as one of the most pervasive threats to the diversity, structure and functioning of marine coastal ecosystems. The loss of habitat structure generally leads to lower abundances and species richness and this often allows opportunistic species to prosper (Airoldi *et al.*, 2008). Habitat destruction and fragmentation can also impair the integrity, connectivity and functioning of large-scale processes leading to decreasing population stability and isolation of communities (Thrush *et al.*, 2006).

In the Mediterranean Sea, coastal habitats such as seagrass meadows, mollusc reefs (created by oysters, vermetids and mussels), coralligenous maerl formations, and macroalgal assemblages on shallow reefs are examples of complex and highly biodiverse and productive ecosystems. They supply food resources, nurseries and shelter for a large array of species that are protected by international conventions, directives and action plans. A meta-analysis of 158 experiments in the Mediterranean revealed that human activity caused adverse impacts on all habitat types. Fisheries, species invasion, aquaculture, sedimentation increase, water degradation and urbanization can all have negative impacts on Mediterranean Sea habitats and associated species assemblages (Claudet & Fraschetti, 2010). Continued loss of habitats to coastal development has triggered several international protective measures such as the development of Marine Protected Areas (MPAs), but their efficacy is questioned (García-Charton *et al.*, 2008; Montefalcone *et al.*, 2009) as habitat loss continues apace. Oligotrophic coastal habitats such as those of in Mediterranean Sea are dominated by slow growing species and intricate food webs. Habitat losses can be considered irreversible, as it would take centuries following the cessation of disturbances for ecosystems to return to their original state.

Overexploitation of resources

Industrialized fishing has severe impacts on species, habitats and ecosystems of Mediterranean (Tudela, 2004). Several fish resources are highly exploited or overexploited (Palomera *et al.*, 2007; FAO, 2012) such as the Bluefin tuna population at risk in Mediterranean (MacKenzie *et al.*, 2009). A number of other organisms are also affected by exploitation and include unwanted by-catch (accidental capture in fishing gear, *e.g.* cetaceans, turtles, etc. Tudela, 2004). Bottom-trawling is a non-selective fishing method that causes a large mortality of discarded benthic invertebrates which can induce biodiversity loss, habitat destruction and biogeochemical changes (Hall-Spencer *et al.,* 1999; Tudela, 2004; Pusceddu *et al.*, 2005; GFCM, 2011). In addition to the general high pressure on fish stocks and other biological resources, another phenomenon called “growth overfishing” is common to Mediterranean fish stocks (FAO, 2012). Growth overfishing relates to the high pressure on young individuals of the stock, in some cases due to consumer demand, and endangers the recruitment (regeneration) of stocks and therefore facilitates situations of overfishing.

Severe population declines have occurred for all top predators during the last 50 years, with the Mediterranean Sea described as the most threatened and endangered sea in the world for cartilaginous fishes (Cavanagh & Gibson, 2007; Bradai *et al.*, 2012). Population declines have also been recorded among marine mammals (such as sperm whales, short-beaked common dolphins, common bottlenose dolphins, striped dolphins and monk seals) that face prey depletion, direct killing and fishery by-catch (Reeves & Notarbartolo, 2006). The Mediterranean monk seal is the most endangered seal in the world with less than 600 individuals currently surviving. Remnant populations are fragmented and declining. The species faces a number of threats (i.e. accidental entanglement, exploitation, persecution and tourism) that caused severe declines in abundance (Karamanlidis *et al.*, 2008), and prolonged starvation due to a lack of prey has been already identified as a major cause of animals death (Mazzariol *et al.*, 2011).

In the 90's, the outburst of the comb jellyfish (ctenophore) *Mnemiopsis leidyi* in the highly eutrophic Black Sea occurred concomitantly with a dramatic collapse of small pelagic fish catches, suggesting a predation pressure by jellyfish on fish eggs and larvae (Zaika *et al.*, 1992). The main cause of this major ecosystem shift was proposed to be an increase in nutrients leading to an excessive bloom which favoured growth of comb jellyfish which out-competed the anchovy (Kideys, 1994). A non-exclusive alternative hypothesis considered the direct role of overfishing on fish stocks depletion with the development of regional industrial fisheries in the early 1970's (Gucu, 2002). The decrease of pelagic predator fish exercised a decrease in top down control and consumption of planktivorous fish. Thus, the abundance of planktivorous fish increased and caused a decline in zooplankton biomass, and a consequent reduced zooplankton-grazing pressure on phytoplankton, leaving the niche open for a rapid development of ctenophore biomass in the Black Sea (Daskalov, 2002). These studies demonstrated that overfishing could indirectly impacted structure and dynamics of ecosystems and increase decline of targeted fish stocks.

From the economic view point, by the late 1980s the fishing industry in the region directly supported almost two million inhabitants (Travis, 1993). Caddy estimates that the losses incurred directly from the crash of the early 1990s cost the basin $240 million USD in direct harvest losses. Combined with the indirect effects on other complementary industries including processing plants and fishing vessel production, Caddy estimated an almost $1 billion USD total loss to the economy of the region (Caddy, 1992). See also Cinar *et al.* (2013) for more details decision making in fisheries in the Black Sea.

Eutrophication and Aquaculture

Eutrophication arises, among others, from agriculture, urbanization, river run-off, industry, tourism and unregulated or uncontrolled aquaculture activities that might cause massive nutrient release in the marine environment. In the ultraoligotrophic Eastern Mediterranean this phenomenon is disrupting habitats and causing community shifts. Eutrophic conditions favor opportunistic species that may increase productivity and fishery catches but may out compete the highly diverse communities of ultraoligotrophic systems.

Considering the exponential human population growth, and the fact that fisheries are in global decline, aquaculture is predicted to increase to meet growing demand (Duarte *et al.*, 2009). Finfish farming can have a number of environmental effects on the surrounding and downstream ecosystems (Holmer *et al.*, 2008). Dissolved wastes increase the nutrient loading of the area and particulate wastes increase sediment deposition in coastal waters. In the benthos sedimentation and organic loading can cause biochemical changes affecting the composition and function of benthic communities (Karakassis *et al.*, 2000), stimulating the growth of undesirable species that produce toxic metabolic waste that can kill species of conservation significance. Large-scale *Posidonia oceanica* losses adjacent to fish farm cages have been reported across the Mediterranean (Pergent-Martini *et al.*, 2006) including the eastern basin (Holmer *et al.*, 2008; Apostolaki *et al.*, 2009).

Improved fish farm management may increase their sustainability although culturing carnivorous fish is still likely to come at environmental costs. Integrated multi-trophic aquaculture (culturing organisms from different trophic levels, mimicking natural ecosystem interactions and producing less waste than monoculture systems) may be key to environmental sustainability of aquaculture practices in ultraoligotrophic waters (Chopin, 2006; Angel & Freeman, 2009). On the other hand, aquaculture activities do require good quality water for farming operations. Therefore, environmental pressures and impacts from other human activities (e.g. tourism, agriculture and urbanization) on the environment surrounding aquaculture farms can have a negative influence on aquaculture itself, and thus the interaction among aquaculture and environment should be monitored through the use of indicators in order to evaluate possible impacts (Fezzardi *et al.*, 2013) The creation of Allocated Zones for Aquaculture (AZA) as suitable areas in which aquaculture is established in order to avoid environmental degradation and negative interactions with other users are minimized or avoided, is considered an immediate priority for the responsible development and management of aquaculture itself (GFCM, 2012 ; Sanchez-Jerez *et al.*, in prep).

Alien species

Warm-water species are increasingly found in the warming Mediterranean Sea due to influx of species from the Atlantic, Lessepsian migration (migration of marine species across the Suez Canal) as well as introduction of alien species by humans (Bianchi, 2007). Most of the 955 alien species so far recorded occur in the Eastern Mediterranean (Zenetos *et al.*, 2010). About 20% of Mediterranean alien species were introduced from biofouling on ship hulls or in ballast tanks (Galil, 2009). However, the majority (about 67%) of alien species came from the Red Sea since the Suez Canal was opened in 1869. More than 600 tropical Indo-Pacific species have been reported entering the Mediterranean Sea where they have established reproductive populations in the Levantine basin and beyond (Coll *et al.*, 2010; Costello *et al.*, 2010). The rate of invasion of species from the Red Sea into the low nutrient waters of the eastern Mediterranean is increasing due to warming (FAO EastMed, 2010). Now nearly half of the trawl catches along the Levantine coast consist of Red Sea originated fish, but whilst some are now targeted commercially, others are detrimental to fisheries. In Cyprus, for example, the invasive puffer fish *Lagocephalus sceleratus* is out-competing native fish and their prey, such as the *Octopus vulgaris* and squid, which are becoming increasingly scarce (Nader, 2012). In this region several other invasive species have caused substantial shifts in coastal ecosystems (Katsanevakis *et al.*, 2009; Öztürk, *in press*).

Chemical pollution

Like all highly populated coastal systems the Mediterranean Sea is affected by numerous anthropogenic contaminants; but their impacts are exacerbated, as it is a restricted exchange, semi-enclose oligotrophic system with waters from the Atlantic only returning 80–100 years later, having circulated the Mediterranean basin in an anticlockwise direction. Marine litter is a major problem in the region, causing obstruction of digestive tracts and contaminant bioaccumulation in many marine animals. Persistent organic pollutants and trace elements tend to bioaccumulate and accumulate in sediments (Gómez-Gutiérrez *et al.*, 2007; Thébault *et al.*, 2008). The biomagnification of them is also a major problem for top predators and could synergeticly impact marine mammal populations when combined with other stressors. For example, in December 2009, a pod of seven male sperm whales were stranded along the coast of Southern Italy. It appears the cause of death was prolonged starvation not from plastic obstruction (even though plastic was found in all dissected individuals) but due to a lack of prey (Mazzariol *et al.*, 2011). High concentrations of pollutants in the tissues of the stranded animals led researchers to conclude that prolonged starvation stimulated the mobilization of highly concentrated lipophilic contaminants from their adipose tissue which entered the blood circulation and may have impaired immune and nervous functions (Mazzariol *et al.*, 2011).

Submarine drilling for oil and gas takes place in the south with exploration now underway in the eastern Mediterranean. About 300,000 tonnes of crude oil are released into the Mediterranean every year (Danovaro & Pusceddu, 2007) and can cause environmental damage, especially when chemical dispersants are used in clean-up procedures. An oil spill in Valencia in 1990 was followed by hundreds of dead dolphins being washed up along the Spanish, French, Italian and North African shores and a year later on the beaches of southern Italy and Greece, thought to be due to disease triggered by immune suppressants in the oil spill (Zenetos *et al.*, 2004). Additionally, large commercial harbours are situated mostly in the northwest Mediterranean and maritime traffic causes noise pollution that adversely affects cetaceans (Dolman *et al.*, 2011).

1.4. General socio-economic aspects of the area

The Mediterranean coasts support a high density of inhabitants, distributed in 22 countries with a growing population of about 470 million (cf. 246 million in 1960), of which 132 million live on the coast (26,000 km in length). In addition, 200 million tourists per year visit Mediterranean coastal countries. During the past one hundred years, the Eastern Mediterranean has been subjected to the effects of two important events, the opening of the Suez Canal in 1869 (discussed below) and the construction of the Aswan High Dam in 1964. Before the construction of the High Dam, nutrient enrichment extended along the Egyptian coast and was detected off the Israeli coast and sometimes off southern Turkey. It provided nutrients for dense blooms of phytoplankton off the Nile Delta (Nile bloom), which in turn provided nourishment for sardines, other pelagic fish and crustaceans. Large declines have been observed in these fisheries in the years following the High Dam construction. Since the late 1980's the recovery of total fish landings in the region reveal that the pelagic ecosystem is adjusting but the mismatch between extremely low primary productivity and relatively high levels of fish production remains a puzzle 'the Levantine Basin Paradox' to scientists (Dasgupta & Chattopadhyay, 2004). Whether this recent increase in fisheries is due to increased fishing efforts, recovery of fish stocks or nutrient enrichments by anthropogenic activities is not yet clear.

2. BIOLOGICAL IMPACTS OF OCEAN ACIDIFICATION

Studies of a natural marine CO_2 vent in off Italy which produce seawater with different CO_2 and seawater pH gradients, including those that may occur in the decades and centuries ahead revealed about a decrease in marine biodiversity at pH levels projected for 2100 (Hall-Spencer *et al.*, 2008). If these results are directly transferable to future Mediterranean Sea biodiversity this would devastate its marine ecosystems. The researchers found that local acidification around the vents disrupts recruitment of organisms from the plankton (Cigliano *et al.*, 2010), and peak summer temperatures increase the susceptibility of some organisms to shell and skeleton dissolution from acidification (Rodolfo-Metalpa *et al.*, 2011) – implying the synergistic impacts of multistressors. Whilst some Mediterranean species have the ability to adapt or cope with acidification, other species appear unable to do so (Calosi *et al.,* 2013). Invasive algal species of *Asparagopsis* and *Caulerpa* can thrive around the CO_2 vents but calcareous systems such as vermetid reefs, coralligene and mussel beds appear to be especially vulnerable in ultraoligotrophic regions where organisms lack food and are therefore less able to allocate resources for coping with multiple stressors (Barry *et al.,* 2011). In contrast, if their habitats are protected from other stressors, some carbon limited organisms, such as seagrasses, may significantly benefit from the increasing availability of CO_2 (Palacios & Zimmerman, 2007) and offer a healthy habitat to numerous species. Nevertheless, Arnold *et al.* (2012) revealed that the seagrass *Cymodocea nodosa* produced less phenolic substances, which tend to inhibit grazing by predators, and have been therefore subjected to greater grazing pressure. While many species could be impacted negatively by ocean acidification other species able to cope with or benefit from ocean acidification could be real “winners” in a future Mediterranean Sea if others stressors are limited.

2.1. At individual level: Look at the ocean acidfication effects on the selected species (science lab evidence and field observations)

The direct effect of ocean acidification on mollusk in the Mediterranean Sea

Species of commercial importance in the Mediterranean Sea have been already subject to several investigations, notably laboratory experiments assessing the species response to increasing pCO_2 in seawater. Following a long-term (~90 days) laboratory exposure of the Mediterranean mussel, *Mytilus galloprovincialis,* to pH 7.3 (Michaelidis *et al.*, 2005), a level projected in the next 300 years, a significant reduction in shell and soft body growth was measured. However, two experiments not located in the Mediterranean but focusing on important Mediterranean species (*Ruditapes decussatus* and *Mytilus galloprovincialis*, (Range *et al.,* 2011 and Range *et al.,* 2012, respectively) showed that pH decreases of -0.3 to -0.7 to pH 7.8 and 7.4) did not lead to a significant growth decrease for these 2 species. However, high alkalinity levels in the Ria de Formosa, Portugal (higher levels than in the Mediterranean) prevented any undersaturation with respect to aragonite in any of the treatments.

Recently, Rodolfo-Metalpa *et al.* (2011) showed that gross calcification rates by *Mytilus galloprovincialis* (as measured by the incorporation of ^{45}Ca) was not impacted by pH during most of the year, except in summer when calcification rates were significantly lower at pH 7.4, suggesting synergetic negative effects of acidification and warming (for review Gazeau *et al.*, 2013). In the frame of the MedSeA project (http://medsea-project.eu; Ziveri, 2012), a year-long experiment has been conducted on the effects of both warming and acidification on *Mytilus galloprovincialis*. Acidification showed no lethal effects on mussels, while all mussels exposed to 3°C above ambient temperature died in August (Temp >27°C). Similarly, ocean acidification had an effect on shell and soft-body growth only in summer in the unperturbed temperature treatment, with significant loss of the periostracum, a protective organic layer covering the outer shell. Results of this experiment are not yet published.

The field observation along natural gradients of CO_2 near Mediterranean volcanic vents highlighted the complex response of molluscs to decreasing pH. Rodolfo-Metalpa *et al.* (2011) reported that limpets had adapted to low pH levels by up-regulating their calcification rates, which counteracted higher shell dissolution rates, an up-regulation at the cost of higher energy consumption. The outer shell layer has the same composition in both species yet the mussels dissolved more slowly than limpets because of a strong periostracum. As a proof of the protective role of the periostracum against ocean acidification damage, dead mussel shells transplanted for three months to mean pH_T 7.2 exhibited dramatic dissolution whereas live mussels maintained their periostracum and were still growing after five months. However, the latter displayed larger areas of damaged periostracum at the umbo than those transplanted to mean pH_T 8.1 suggesting a decreased ability to repair periostracum at low pH and limit shell dissolution. Both species were able to precipitate calcium carbonate in undersaturated seawater. Adult limpets were found at the CO_2 vents at mean pH_T 6.5, although in lower abundances than outside the vents. Their shells were highly corroded as they were permanently exposed to undersaturate conditions ($\Omega c = 0.39$) and lacked a protective periostracum. Shell dissolution was pronounced on the oldest parts of large individuals. Transplanted limpets grew a distinctive new shell rim after only one week, both at mean pH_T 8.0 and 6.5, as they grew to conform to the rock surface.

The ocean acidification impact on molluscan calcifiers is not limit to growth and calcification as several physiological processes are affected by hypercapnia. Michaelidis *et al.* (2005) showed that long-term hypercapnia at pH 7.3 caused a permanent reduction in haemolymph pH and suggested that these organisms increase haemolymph bicarbonate levels derived mainly from enhanced shell dissolution in order to limit the degree of acidosis. In contrast, although intracellular pH decreased significantly with environmental hypercapnia on the short-term, it was restored to normal levels in most tissues after several days of exposure. The decrease in haemolymph pH was suspected to be the main reason of the decrease in oxygen consumption rates as observed at low pH, due to the inhibition of net proton transport across the cell membrane, a metabolic depression that is consistent with results from experiments performed on other marine invertebrates (e.g. Pörtner *et al.,* 1998). Increased rates of ammonia excretion and associated decreases of O:N ratio suggested that the organisms exposed to low pH conditions increased their use of proteins as metabolic substrates. This could be responsible for damaging their cellular protein pool and therefore contribute to the observed drop in somatic growth.

Recruitment of organisms from the plankton is impaired in many groups as the larval stage is especially vulnerable to the effects of ocean acidification on their development - this appears to be especially true for molluscs with implications for the shellfish industries (Cigliano *et al.,* 2010). In their recent review, Gazeau *et al.* (2013) reported that embryonic and larval stages mainly respond negatively to elevated $p\mathrm{CO}_2$ regarding survival, development rate, growth and calcification. In oyster and mussel, studies showed that the negative effects of ocean acidification coincided with the beginning of the shell formation (trochophore stage), with no real impacts detected prior to this time and the decrease of larval development and growth is more correlated to carbonate ions availability than to pH or aragonite saturation state (Gazeau *et al*., 2011). Although mollusk embryo and larvae responses to $p\mathrm{CO}_2$ are not fully understood, early-life stages vulnerability has to be identified as a bottleneck for population dynamics, and a concern for exploited mollusk (Dupont *et al*., 2010).

The direct effect of ocean acidification on fish in the Mediterranean Sea

Based on the sparse current knowledge, adult fish are not directly impaired by ocean acidification as their physiological performance allows them to cope with extracellular acidosis caused by increasing $p\mathrm{CO}_2$ (*e.g.* Melzner *et al*., 2009). However, it has been shown that ocean acidification can interfere with crucial sensory behaviour in juvenile coral reef fish (Munday *et al*., 2009; Simpson *et al*., 2011; Bignami *et al*., 2013). In addition, the long-term consequences of the enhanced energy cost for acid-base compensation on fish fitness remained unknown, considering that hypercarpnia will limit aerobic scope and thus may influence individual performance (Pörtner and Farrell, 2008).

A few direct effects of ocean acidification have been found on early-life stages of fish, which are considered as most vulnerable because of the non-maturity of their physiological systems and thus limit their acclimation capacities (Pörtner and Farrell, 2008). A decrease of survival and growth rate has been observed in estuarine fish (*Menidia beryllina*) when high-CO_2 (1000 ppm) exposure occurred just after egg fertilization, potentially affecting recruitment success at the population scale. Altered behaviour and otolith growth under high $p\mathrm{CO}_2$ have been also highlighted, although responses are species-specific (Checkley *et al*., 2009; Munday *et al*., 2011ab). Whilst there are still few studies on the impact of ocean acidification on early life stages of fish there are indications that an increased $p\mathrm{CO}_2$ can negatively affect the metabolism and development of embryos of the Atlantic herring (a cold-water clupeid fish), *Clupea harengus* (Franke and Clemmensen, 2011).

In the northwestern Mediterranean Sea, landings of warm-water clupeid anchovies and sardines is negatively correlated with low SST and high river runoff suggesting that reproduction and recruitment success is affected by high temperature anomalies and land-based nutrient-related productivity of the coastal area (Martin *et al*., 2012). Therefore, this implies that climate change including ocean acidification may indirectly impact small pelagic populations in Mediterranean Sea. Nevertheless, there is a strong need to improve knowledge on the potential impact of CO_2 conditions on the early life stages, especially in the Mediterranean Sea where no data are available at the moment.

2.2. At population/community level: Interdependence, food-web and resilience

In the coming decades ocean acidification is expected to significantly alter the biodiversity, structure, ecology and biogeochemistry of the Mediterranean Sea ecosystem as a consequence of a variety of different biological sensitivities and responses from organisms and populations. Volcanic carbon dioxide vents are being used as natural laboratories to study the effects of ocean acidification on a variety of coastal ecosystems as well as individual organisms (refer to previous section). Off the islands of Vulcano and Ischia, Italy, vents enrich seawater with CO_2 and this changes the seawater carbonate chemistry and alters calcification, recruitment, growth, survival in many species and how species interact with each other. *In situ* observations highlighted that many species of macroalgae, seagrass, corals, polychaetes, crustaceans, molluscs and bryozoans are remarkably tolerant of long-term exposures to high and variable carbon dioxide levels at the vents (e.g. min 309, mean 854, max 1908 μatm $p\mathrm{CO}_2$). However, a fall in mean pH 8.1 to mean pH 7.7 has detrimental effects on the recruitment of benthic organisms from the plankton with 30% fewer species in adult populations at mean pH 7.7 than in adjacent areas at mean pH 8.1. Important groups, such as coralligenous systems, vermetids, and sea urchins are especially susceptible to increased levels of carbon dioxide levels and are outcompeted by non-calcified organisms. This *in situ* work on effects of CO_2 on coastal marine communities strengthens concerns, based on model predictions and laboratory experiments, that ocean acidification will likely combine with other stressors to cause declines in Mediterranean marine biodiversity and lead to shifts in ecosystem structure.

Ocean acidification impact on habitat-building species

Photosynthetic organisms, using CO_2 as a source for organic matter production, could potentially benefit from its higher availability. While Israel and Hophy (2002) showed that a pH of 7.8 does not have any effect on growth and photosynthesis in a wide range of Mediterranean algae, Invers *et al.* (1997)

reported that this level of acidification enhanced photosynthesis in the important habitat forming Mediterranean seagrasses *Posidonia oceanica* and *Cymodocea nodosa*. Field studies at the proximity of shallow volcanic CO_2 of Vulcano and Ischia showed that Mediterranean seagrasses and certain seaweeds are able to benefit from elevated CO_2 levels (Hall-Spencer *et al.*, 2008; Porzio *et al.*, 2011; Johnson *et al.,* 2012) and extend their cover area to the detriment of the diversity and abundance of calcareous algae. Calcifying Coralline algae can also be important habitat formers and were also found to be adversely affected by elevated pCO_2 conditions, particularly when combined with high temperatures (seasonal temperature +3 °C; Martin and Gattuso, 2009). More recently, Kroeker *et al.*, (2013) showed that calcareous species might be physiologically able to persist in pH condition predicted for the near-future ocean but suffer from the development of a higher competitive ability of fleshy, non-calcareous seaweeds. Overall, current studies indicate that ocean acidification will cause major shifts in the microalgae and seaweed communities. The potential loss of some of these organisms is a great concern as they form important habitats for fish, shellfish and a wide range of other organisms.

Results obtained in the framework of the MedSeA project suggest dramatic changes across ecosystems and taxa under ocean acidification and warming conditions. Some habitats such as the vermetid reefs along the Levant coast are facing extinction, which is likely to result in major loss of biodiversity and shore erosion. Other habitats such as sea grass meadows are expected to suffer from elevated seawater temperature and invasion by non-indigenous algae species, which benefit from increased pCO_2 and elevated temperature. The slow growth or even extinction of key calcifiers may detrimentally affect major bio-construction on vermetid reefs and coralligene reefs where these supply the cementing calcium carbonate that keeps these reefs intact (Fine *et al.*, subm.; Milazzo *et al.*, in press). Whilst calcified organisms generally fare badly as CO_2 levels increase, some can proliferate in an uncalcified form (e.g. *Padina* spp., Johnson *et al.,* 2012). Calcifying corals, that form important habitats for fish, supporting their own fisheries also attract recreational tourism (Hilmi *et al.,* 2012) and support local economies appear to be particularly vulnerable (Rodolfo-Metalpa *et al.,* 2011). For example, it has been recently demonstrated that there are detrimental effects of ocean acidification on the economically important Mediterranean red coral endemic species *Corallium rubrum,* mainly due to the elevated solubility of its Mg-calcite skeleton (Bramanti *et al.*, 2013).

First results based on observations and manipulations obtained in the framework of the MedSeA project are clearly showing that no benthic habitat will benefit from elevated temperature and increased pCO_2 (Fine *et al.*, in prep.). Both calcifying and non-calcifying engineering species are likely to suffer under warming and acidification. This in turn will lead to malfunction of the respective habitats and have knock-on ecological effects, limiting the biodiversity and functional diversity of ecosystem, *i.e.* limiting resources for targeted species and nursery grounds and potentially altering the sustenance of fish stocks.

Finally, recent studied performed in sedimentary habitatsin the natural CO_2 gradients off Vulcano, Italy, have revealed increased ocean pCO_2 is associated with changes in sediment bacterial community composition but that most of these organisms are resilient (Kerfahi *et al.*, 2014).

Impact on trophic web

Studies have highlighted a possible shift from large phytoplankton towards the smallest pico- and nano-plankton as a result of future ocean acidification – see Riebesell *et al.* (2013). Considering that the Mediterranean is already mainly dominated by nanoplankton (Oviedo *et al.*, 2014), such a substantial change in the base of the pelagic food web will have direct consequences for the structure and functioning of the higher levels of food web. Moreover, field studies at the community scale highlighted that decreasing pH tends to lead to a decrease in the species richness and biomass causing a simplification of the trophic web functioning (Kroeker *et al.*, 2011; Ziveri *et al.* in revision). This shift of community to a few generalist species could lead to another cause for concern, that is a proliferation of non-calcifying cnidarians (jellyfish and anemones) resilient to or benefiting from warming and acidification (Winans and Purcell, 2010; Suggett *et al.,* 2012). In the Black Sea, the balance for trophic dominance between small pelagic fish and gelatinous species is tenuous as shown by the huge decline of fisheries landings in 1990's and increase in comb jellyfish (Shiganova, 1998). Moreover, jellyfish outbreaks can split the fishing nets, ruin the quality of the catch and cause massive death of farmed fish when stinging filaments released in water column irritate the fish gills and result in hemorrhage and subsequent suffocation (Purcell *et al.*, 2007). In the Mediterranean Sea, frequency of outbreaks of the jellyfish *Pelagica noctiluca* can be linked with warming (Licandro *et al.*, 2010) but the contribution of ocean acidification to jellyfish blooms is still under debate (*e.g.* Attril *et al.*, 2007; Richardson et Gibson, 2008).

Combined impact with toxicants

Concomitantly with increased eutrophication and stratification of the Mediterranean Basin, ocean acidification is expected to foster Harmful Algal Bloom (HAB) in coastal waters (Rosa *et al.*, 2012). Proliferation of these harmful microalgae can both cause damage to the environment directly affecting exposed organisms and threaten human health through contaminated seafood consumption (Erdner *et al.*, 2008). Temperature appears as the main factor driving harmful algae abundance, as observed for ciguatoxin *Gambierdiscus spp* (Chateau-Degat *et al.*, 2005) or saxitoxin *Alexandrium catenella* (Moore *et al.*, 2010). In the Mediterranean Sea, the palytoxin-producing dinobiont *Ostreopsis ovata* is extending its distribution, with definite consequences on human health (irritation, cough, fever and respiratory problems; Mangialajo *et al.*, 2008). Moreover, *Gambierdiscus toxicus*, the main causative agent of ciguatera poisoning, normally has a tropical or subtropical distribution has recently been reported in waters around Crete. Increased temperatures are thought to trigger proliferation of these harmful algae. While there are few studies investigate the potential impact of ocean acidification on the HABs, it has been recently demonstrated that CO_2 combined with limited nutrient enhanced karlotoxin and domoic acid production by *Karlodinium veneficum* (Fu *et al.*, 2010) and *Pseudonitzschia fraudulenta* (Tatters *et al.,* 2012), respectively.

Ocean acidification and warming will occur in a background of chronic contamination of the coastal area through human discharges of contaminants. The changes of seawater chemistry caused by increased CO_2 can modify the bioavailability of contaminants such as trace elements (Millero *et al.*, 2009). As a consequence of acidification, the bioaccumulation and contaminant levels of metals in organisms could change (Lacoue-Labarthe *et al.*, 2009, López *et al.*, 2010) and the toxicity of polluted sediment or shallow water on invertebrates increased (Roberts *et al.*, 2013, Ivanina *et al.*, 2013). Vulnerable developmental stages, such as bivalve early life stages, might be particularly impacted by these combined stressors (Han *et al.*, 2013) further challenging recruitment of critical stage that aquaculture depends on.

Summary

The sparse information available on the effect of ocean acidification mainly focus on the individual response of organisms of high economic interest, and especially highlight a reduction of growth and calcification with elevated pCO_2, in bivalves including mussels and oysters that count for 75% of the total shellfish production in Mediterranean Sea. If these results are transferable to future aquaculture production it implies a decrease in production rate and that shell fisheries might experience mass mortality of larvae or juvenile bivalve that could compromise the durability of this activity. Considering that the ocean warming already challenges organisms in Mediterranean and Black Seas, the implementation of adaptive management (*e.g.* transport of oyster culture from hot inshore waters to colder offshore water during summer, or other moving strategy; selection of resistant strains) appears inevitable but this might, in turn, impact production costs.

There is insufficient evidence to allow any conclusion with regard direct impact of ocean acidification on fish production, or their acclimation or adaptation capacities to this stressor, but it is probable that fish populations may be impacted through changes to the habitats and food web that they depend on. The Mediterranean Sea benefits from natural CO_2 vents that give evidence of a shift in habitat-building species (e.g. coralline algae *vs.* filamentous seaweed), a decrease of biodiversity and a simplification of the food web with increasing acidification. Nevertheless, these natural laboratories are continuously linked with biota from non-acidifying waters away from the vents that could provide a continuous supply larvae and juveniles for recruitment in the vent areas with high CO_2 and low pH and therefore mask the full ecosystem response to ocean acidification. Thus there is a need to continue the investigations taking into account the ecological interactions between species, and the potential synergism of acidification with others stressors.

3. ECONOMIC IMPACT OF OCEAN ACIDIFICATION

Fisheries and Aquaculture activities in Mediterranean and Black Seas represent 1% of the world landings and 2% in term of the economic value. While fisheries catch remain quite stable since 1990’s, aquaculture production is constantly increasing (Figure 4).

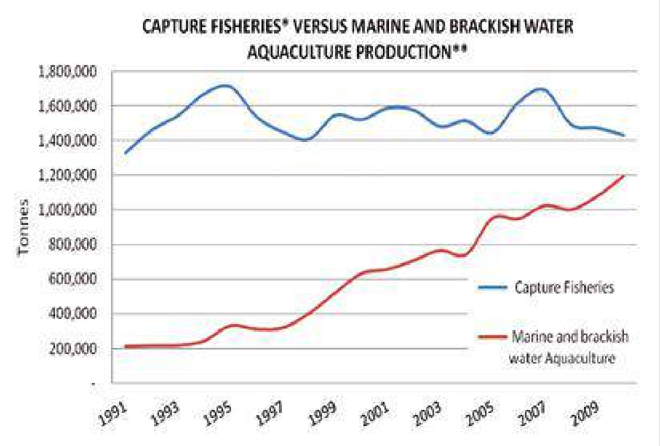

Figure 4:

Trends of capture fisheries and aquaculture production in countries of the General Fisheries Commission for the Mediterranean (GFCM) from 1991 to 2010.
Data source: (*) FAO Capture Production in GFCM statistical area (release data: February 2012) – (**) Production in GFCM countries (aquaculture from Atlantic areas excluded) – SIPAM-FAO Aquaculture Production 1959-2010 (Released date: March 2012).

3.1. Current data: Regional trends on landings on selected commercial fish species

Industrial fishing sector

Small pelagics account for approximately 50% of the total Mediterranean catch (about 1.5 million tonnes in 2000’s). Anchovy *(Engraulis encrasicolus),* and sardine *(Sardina pilchardus),* are the most abundant with 59% and 16% of small pelagic fish catch, respectively. Other small pelagic fish are sprat *(Sprattus sprattus),* sardinella *(Sardinella aurita)* (see Figure 5) and Azov sea sprat *(Clupeonella cultriventris).* In the 1990’s some of these species collapsed in the Black Sea due to a combination of different factors such as fishing pressure and a jellyfish bloom (Boero, 2013). In the Black Sea 70% of anchovy are caught by small- scale fisheries from Turkey. Other fisheries resources include demersal species (29%), crustacean (6%) and molluscs with cephalopods (10%). Within the last group, it is worth noting the spectacular increase in catches of the bivalve striped venus clam, *Chamelea gallina*, (around 40,000 tonnes) mainly in the Adriatic (Figure 6). Small-scale fisheries dominate (>60%) the fishing sector in the Mediterranean and Black Seas.

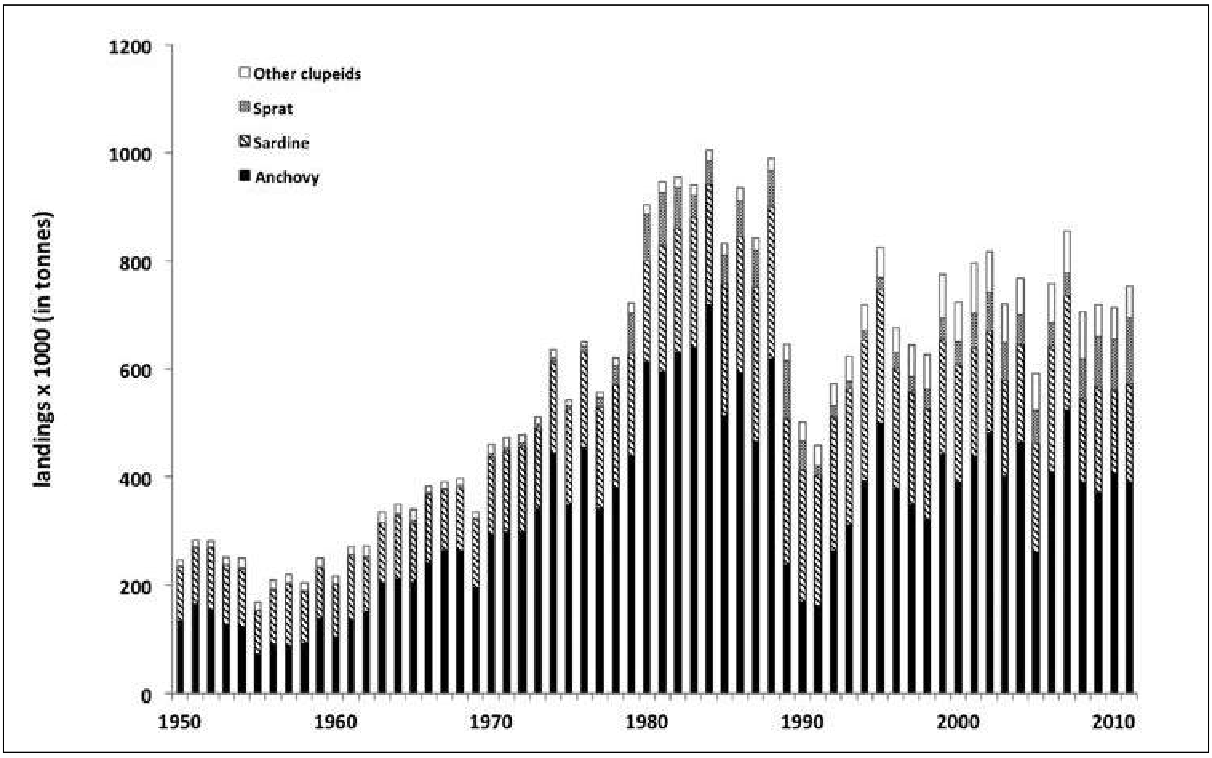

Figure 5:

Trends of landings of anchovy *(Engraulis encrasicolus)*, sardine *(Sardina pilchardus)*, sprat *(Sprattus sprattus)* and other small pelagic in Mediterranean and Black Sea from 1950 to 2010.
Data extracted from “Global capture production” databases from FAO with FishStatJ software.

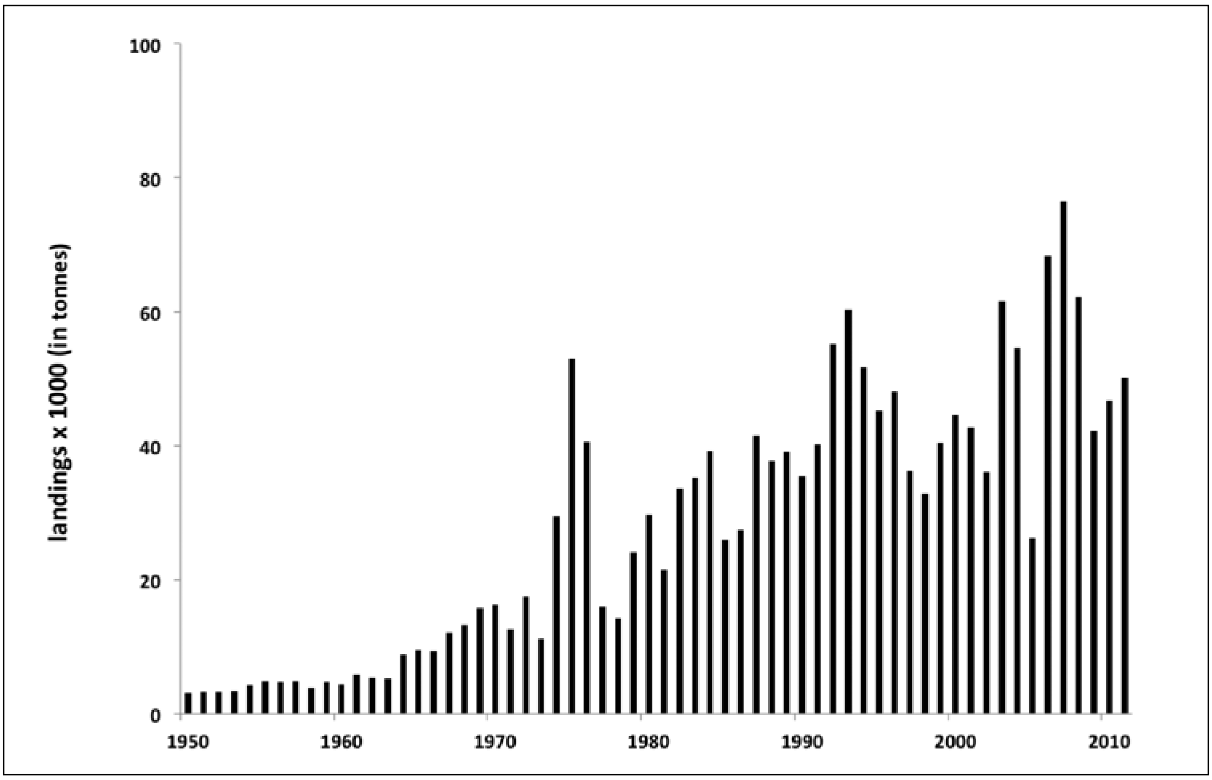

Figure 6:

Trends of landings of the clam *Chamelea gallina* from 1974 to 2010 (expressed in tonnes). Clams are mainly collected in the Black Sea and Adriatic Sea.
Data extracted from “Global capture production” databases from FAO with FishStatJ software.

Aquaculture

Marine and brackish aquaculture is a growing sector in the Mediterranean and Black Sea countries and it plays an important role in responding to the demand for seafood and delivering key social and economic benefits. Aquaculture in these countries covers different FAO statistical areas. In particular the marine environment is referred to the statistical area FAO 37 (Mediterranean and Black Sea marine water), FAO 27 (Northeast Atlantic marine water, for France and Spain) and FAO 34 (Atlantic eastern central marine water, for the production of Morocco). As for freshwater and brackish environments the FAO statistical areas concerned are: FAO 01 (African inland water, for the production of Egypt, Libya, Tunisia and Morocco), FAO 04 (Asia inland water, referred to the inland production of Cyprus, Israel, Lebanon, Syria and Turkey), and FAO 05 (Europe inland water, for Spain, France, Italy, Malta, Slovenia, Serbia, Croatia, Montenegro, Albania and Greece).

There are more than 67 different species of fish, molluscs and crustaceans both from marine and freshwater currently farmed in the Mediterranean and Black Sea countries, with the production of fish and molluscs dominating and the production of crustaceans still limited.

Among the species of farmed finfish, the production of gilthead seabream (*Sparus aurata*) has risen rapidly up from 3,833 tonnes in 1990 to 143,295 tonnes in 2010 (worth approximately US$ 785 million). The European seabass (*Dicentrarchus labrax*) has also recorded a positive growth from 2,944 tonnes in 1990 to 131,509 tonnes produced in 2010 (about a value of US$ 786 million). In 2010 the main producers of gilthead seabream were Greece (42.8%), Turkey (20.4%) and Spain (13.3%), whereas the top three producers of European seabass included Turkey (39.5%), Greece (27.5%) and Egypt (12.4%). Among the emerging finfish species in Mediterranean aquaculture the meagre (*Argyrosomus regius*), whose production started in 1997 in France and Italy. In 2010 meagre was produced in Egypt (by far the main producer with 81% of total production), Spain, France, Malta, Italy, Cyprus and Croatia (GFCM, 2013).

In the Mediterranean Sea, oyster farming has been practiced by the ancient Romans, near Naples (Italy), as early as the 1st century BC. The species that was cultivated at that time was the European flat oyster (*Ostrea edulis*) and has been cultivated for centuries. Recently, in the 1970s, many flat oyster populations in the Mediterranean (as well as in the Atlantic) suffered massive mortalities due to infection by pathogenic protozoan parasites, this species has been progressively replaced by the Pacific cupped oyster (*Crassostrea gigas*), as it is more resistant. In recent times, bivalve yields have greatly increased between the 1950's and the 1990's and are now stabilizing at around 180,000 tons yr^{1} (Fig. 7, A). Italy is by far the biggest producer, representing 67% of the Mediterranean production, followed by Greece and France (14%; Fig. 7, B. Although Spain is a major producer of bivalves in Europe, the vast majority of its production is located on the Atlantic coast. The most cultivated species nowadays in the Mediterranean Sea is the Mediterranean mussel (*Mytilus galloprovincialis*) that represents almost three quarters of the total Mediterranean shellfish production (120,000 vs. 160,000 tons yr^{1}; Fig. 7, C). Farmed allochthonous species such as the Japanese carpet shell (*Ruditapes philippinarum*; about 35,673 tons yr^{1} with around 98% in Italy) and the Pacific cupped oyster are the other important cultivated species (8,000 tons yr^{1} and 300 tons yr^{1} by Spain and France.

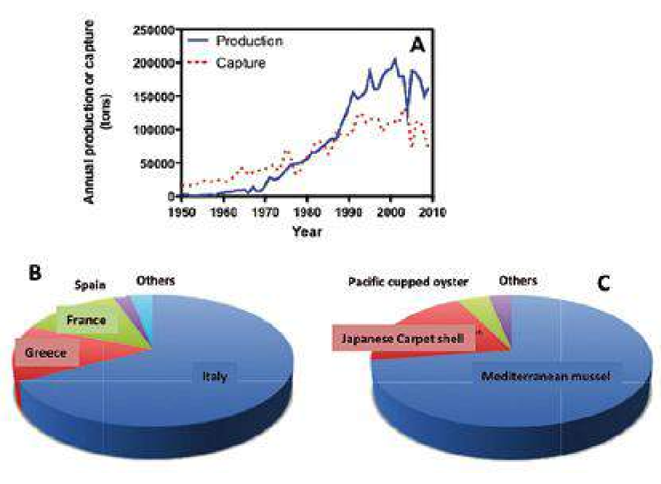

Figure 7:

Bivalve's production from aquaculture activity in Mediterranean Sea.
Data extracted from "Global aquaculture production" databases from FAO.

3.2. Role of fisheries in the economy: local consumption or contribution to trade and industry, employment and level of intermediate/final product (including a regional food security dimension and distributional effects)

Capture fisheries and aquaculture in the Mediterranean and Black Seas play an important role in terms of contribution to economic development and also provide central sources of food and employment for coastal communities. Capture fisheries are characterized by a wide range of fishing activities and type of fleets adapted to the different ecosystems and targeting different fisheries species. Aquaculture development in the Mediterranean and Black Seas, are at different levels of maturity and encompasse a wide range of farming technologies, farmed species and ecosystems. Capture fisheries and aquaculture in the Mediterranean Sea directly employs about 373.000 (250,000 and 123.000 in fisheries and aquaculture, respectively) for primary sector and employs about 210,000 people for secondary sector (Sacchi, 2011).

3.3. Benefits beyond fisheries

The benefits supplied by the marine environment to human are enormous and goes far beyond that supplied through fisheries and aquaculture. For instance, the large marine biodiversity, long coast line and pleasant climate supports sea based recreational activities and promotes tourism activities, these are very well developed in the Mediterranean Sea (see below). The species richness provides "use value" through exploitation of marine organisms such as sharks, algae and sponges which supply a large variety of bioactive metabolites some of which are used to treat human diseases and, a non-use value as bequest and existence value (Rodrigues *et al.*, 2013). In the context of economic valuation of bequest and existence value of marine organisms, Langford *et al.* (1998) report a non-market valuation study in Greece to estimate the public's willingness to pay (WTP) for conservation of the Mediterranean monk seal (*Monachus monachus*) in the Aegean area – see also Nunes and van den Bergh (2001) for other studies on bequest and existence value of marine species. The monk seal is classified as the most endangered seal species in the world (IUCN 2013) since it has suffered much from human pressure, in particular from fishermen who their fishing gear damaged. A recent review on non-market economic valuation studies has been carried out (Remonundou *et al.* 2009). The richness of the Mediterranean Sea biodiversity implies that this region can provide a wide range of food (high-quality protein, minerals and vitamin D and omega-3 fatty acids) with antioxidant properties and cardio and cancer protective effects and ornamental resources. Consequently, the biodiversity provide intrinsic capacities to favour adaptation of species (genetic diversity), resilience of ecosystem (specific richness within ecological guilds) and adaptation of dependent-population fostering shifts of fisheries targets.

3.4. Scenarios of ocean acidification and evaluation of the respective socio-economic impacts effects

The International Panel on Climatic Change (IPPC, 2013) has identified new scenarios, Representative Concentration Pathways (RCPs) that take alternative futures in global greenhouse gas and aerosol concentrations as their starting point. The IPCC has been able to model future ocean acidification, as well as other climate variables, for each RCP. It is clear that future acidification depends on the amount of CO_2 emitted to the atmosphere. If society does not curb CO_2 emissions rapidly and urgently the global ocean will become more acidic and warmer. This, in turn, will have an impact marine ecosystems structures and functions and therefore an impact on the marine systems goods and services, including fisheries. In this context, ocean acidification is considered a compounding threat to the sustainability of capture fisheries and aquaculture development and therefore impacting the global economy and our society. Furthermore, there is a general scientific consensus that ocean acidification will bring along with it significant welfare impacts in the Mediterranean and Black Sea areas, including direct and/or indirect impact in many risk-prone areas and vulnerable communities (Rodrigues *et al.*, 2013). In particular, ocean acidification will have consequences for shell-producing organisms at different stage of their life cycle and therefore mollusc aquaculture will also be affected. Furthermore, such impact could also be worsened by an increase of water temperature (De Silva and Soto, 2009; De Young *et al.*, 2012). Rosa *et al.* (2012) stated that, further studies investigating the adaptive response of calcareous organisms to ocean acidification and concurrent increase in seawater temperature, are needed in order to make an accurate socio-economic and biological assessment of their impact. The degree of vulnerability of coastal communities and possible adaptation measures to strengthen their resilience still need to be defined and assessed. It seems however, that potential impacts from climate change and ocean acidification are not yet perceived as a compelling risk among coastal communities, farmers and decision-makers.

4. EMPIRICAL EVIDENCE

4.1. Capture and aquaculture production

The high intensity of capture fisheries in the Mediterranean Sea represents a serious threat to the maintenance of the fish stocks (EEA, 2002). Over exploitation is expected to complicate the assessment of ocean acidification impacts as the former type of stressor may dominate the latter in the short run. Ocean acidification is an additional stressor that is capable of threatening the resilience of fisheries. The effects of acidification on aquaculture will strongly depend on the degree to which aquaculture production may be controlled and sheltered from its negative impacts. Some aquaculture marine species such as bivalve molluscs need to spend certain periods of their culture in open water, or they are fed by other organisms that grow in open water (Narita *et al.*, 2011). In both cases there is possible impact from acidification. For some Mediterranean countries, sea food is an important part of their income and nutrition, a fact that highlights the need to consider the ocean acidification impacts on this sector as well its adaptive capabilities (Cooley *et al.,* 2012). Assessments so far mostly involve market analysis as acidification has the potential to enforce revenue changes through alterations to fisheries. Through the identification of the commercial species more likely to be affected it is possible to assess their economic value and the potential economic impact. This logic is followed, for example, by (Cooley and Doney 2009) in which commercial marine species are classified into calcifying organisms, related predators and supposedly uninfluenced species. Based on the classification of the most vulnerable commercial species, estimates of physical change in capture and aquaculture productivity under future scenarios of ocean acidification, which include modelling responses at the ecosystem-level, allow for the quantification of possible decreases in the value.

4.2. Coastal tourism and recreation

International tourism in the Mediterranean is characterized 306 million arrivals annual, around one-third of all international tourists arrive in the Mediterranean, making it the world's most visited region (UNWTO, 2012). This economic activity brings 215 billion euro a year in export earnings (UNWTO, 2013). International tourism is also an important in the Black Sea, which registers around 58 million arrivals annual. Turkey, with its 7200 km of coastline in the Black Sea, contributes with ¾ of the total arrives and this economic activity brings 25.6 billion euro a year in export earnings to Turkey (UNWTO, 2013). The coastal tourism sector and the related recreational activities (e.g. swimming, diving, and recreational fishing) could be affected by environmental changes related to ocean acidification. For example, jellyfish and harmful algal outbreaks may cause health problems for swimmers, and the reduction of red coral populations may affect recreational divers and threaten tourism. A socio-economic survey, carried out in July 2012, captured the welfare impacts of an invasive alien jellyfish outbreak (*Rhopilema nomadica*) among coastal recreationists in Israel. Results indicate for the coastal population of Israel, annual benefits of seaside visits range between 20.1 to 30.3 million and 39.1 to 58.7 million US$, respectively. The jellyfish outbreaks significantly affect beach recreational behaviour during swarming. The monetary value of this impact is estimated up to 5.2 million US$ a year (Bella *et al*. subm.). A similar socio-economic study was carried out in Catalonia, which is among the most visited coastal area in the Mediterranean – registering 263,7 million beach recreational visits in 2011 (Cataluya Turistica en Xifres, 2011, Nunes *et al.,* 2013). According to estimation results, the underlying welfare impact from jellyfish outbreaks ranged up to 440 million US$ a year. This amount corresponds to 9% of the tourism expenditures of the Catalan population in 2011, and expresses the significant welfare gains associated with a reduction of jellyfish outbreaks in this area (Nunes *et al*., in revision).

5. POLICY RECOMMENDATIONS

5.1. Recommendations in terms of policy action (mitigation / adaptation) taking into account both the costs/benefits of policy action as well as the costs of policy inaction

In ultraoligotrophic environments such as the Mediterranean Sea, where resources are scarce, organisms are particularly vulnerable to multiple stressors. Climate change is underway and its impacts may continue for many millennia after cessation of anthropogenic CO_2 emissions (Tyrrell, 2011). Warming increases stratification that reduces the transfer of nutrients from below the thermocline. Deoxygenated regions are expanding and acidification may impair ecological functioning (Byrne, 2011). In addition to climate change, marine litter continues to accumulate and can cause starvation (e.g. of birds and turtles), contaminant bioaccumulation, alien species transportation and entanglement are all added stressors. The enclosed nature of the Mediterranean and extensive populated coastline means that it faces additional threats due to the close proximity to Man. Toxic pollutants bioaccumulate and impair the normal physiological functions of organisms causing for example, cetacean strandings. Invasive alien species are spreading and are competing, predating and infecting indigenous species and altering ancient food webs. Marine fish stocks are overexploited with most top predators in decline. Eutrophication decreases water quality, which can add pressure on coastal systems subjected to habitat loss and degradation.

It is clear that past methods have failed to ensure environmental sustainability yet there are several reasons to be optimistic. It is now realized that marine ecosystem degradation is a global concern. International efforts to reduce rates of biodiversity loss have led to numerous agreements, conventions or other legal instruments that are coming into force. Such international agreements form the basis of the long-term collaboration that is necessary for improved environmental management. For example, the Kyoto Protocol came into force on 2005 and commits the 191 member states to tackle the issue of global warming by reducing greenhouse gas emissions. Annex 1 countries pledged to reduce their emissions by 5.2% from 1990 levels by the end of 2012. The United Nations Convention on the Law of the Sea (UNCLOS) signed by 161 countries helps control pollution and set guidelines for the protection of the environment and the management of marine natural resources in the world's oceans. Inter-governmental organizations, such as the General Fisheries Commission for the Mediterranean (GFCM) and International Commission for the Conservation of Atlantic Tunas (ICCAT), are charged with the conservation of stocks, the latter specifically for highly migratory species. In Europe, the Marine Strategy Framework Directive aims to achieve healthy waters by 2020 with an unprecedented level of cooperation between countries in developing a network of MPAs. Monitoring of environmental quality, biodiversity and long-term changes in community structure through an international coordinated network of MPAs is approaching reality. Cautious use of Integrated Coastal Zone Management and Environmental Impact Assessments can help slow the rate of coastal environmental degradation. International partnerships like the Global Ocean Biodiversity Initiative (GOBI) are promising and the identification of Ecologically or Biologically Significant Areas (EBSAs) in the open oceans and deep seas is well underway. It is clear that these international efforts are required to slow the rates of marine environmental degradation.

There are now ample examples where interventions have had positive environmental outcomes. A primary goal among nations should be to raise awareness of effective marine environmental protection. For example, the most viable option to reduce litter is to reduce its production in the first place and then to improve reuse and recycling through enhanced environmental awareness. There is now scientific clarity that ocean warming, acidification and deoxygenation are underway due to anthropogenic CO_2 emissions so the primary mitigation strategy is to reduce these emissions (Gruber, 2011). There are reasons to be optimistic about improved management of ultraoligotrophic systems as a growing awareness of their value is being accompanied by shifts towards more sustainable ways of obtaining resources (e.g. marine renewables) and dealing with wastes (e.g. carbon capture and storage).

5.2. Governance and policy mechanisms

The empirical evidence derived from the work of a couple of EU projects, which are about to be completed, reiterates the importance of the consultation processes among the different stakeholders in the approach, discussion and evaluation of different policy mechanisms. This reinforces the inclusive nature of the measures adopted and therefore facilitates the adoption of the policy or management scheme under consideration. In this respect, within the MedSeA, a EU project on ocean acidification in the Mediterranean Sea, a consultation group involving key scientists, marine and coastal managers, conservation practitioners, industry representatives, science policy advisors and policy makers, and other stakeholders and end-users, mainly from countries bordering the Mediterranean Sea was developed. This group promotes the consolidation of a common working language. More than this, this group reinforces the institutional setting and this way directly also contributing to the success of the policy or management response. Indeed, institutional settings can often determine the success or failure of a policy action (Millennium Ecosystem Assessment, 2005).

In the same line of thought, empirical studies that focus on the economic valuation of ocean acidification impacts on the human well-being need to be conducted with a cognizance of the local political, social, economic and institutional framework; but more than this, it then needs to be determined how best to embed these values into the decision-making process that exists within this framework. In another EU project, Vectors, a set of socio-economic valuation studies were implemented in the Mediterranean Sea so as to evaluate the impacts of jellyfish on beach recreationists (Galil *et al.,* 2013; Nunes *et al.,* 2013) inform us that from a cost-benefit-analysis, it is recommended to invest public financial resources in adaptation policy mechanisms, including the use of real time information systems which data is treated and adapted for use next to the general public. The *liaison* is possible through the use of internet and social media applications, including the development of ad-hoc, free downloadable applications from smart phones – see Marambio *et al.,* 2013).

6. SUGGESTIONS FOR FURTHER RESEARCH NEEDED TO FILL THE GAP BETWEEN NATURAL SCIENCES AND ECONOMICS

As the Mediterranean and Black Seas are known to be threatened by increasing $p\mathrm{CO}_2$, it becomes increasingly essential to assess the socio-economic value of these important systems, including ocean acidification impacts on fisheries and aquaculture. In 2011 an EU project (MedSeA) was launched to shed the first light on the complex Mediterranean system both dealing with ocean acidification and increase seawater temperature (medsea-project.eu) and attempting to link life sciences and socio-economics. However, this is only a first attempt and much more work is needed, for both the Mediterranean and the Black Seas, to identify, characterize and model marine ecological functions (including ecosystem processes, functions and controlling components). Additionally, a greater understanding of how these ecosystems and the goods and services they provide society, are affected by ocean acidification. For example, whilst information available on the status of commercial fish stock, produced annually by the regional fisheries management organisations such as GFCM and ICCAT key species is useful additional information is needed on the impact of ocean acidification on pelagic fish for the Mediterranean and Black Seas as well as for the key species, food webs and ecosystems upon which they depend. Impacts should also be investigated on the larval stage for the species used in marine and brackish aquaculture. Furthermore, we endorse a multi-stressor research based approach that seeks to disentangle local, regional *vs* global stressors which is essential for choosing/ranking policy instruments.

Due to the geographical variations of physico-chemical conditions in Mediterranean and Black Seas, we suggest enhancing our scientific knowledge by setting up long-term, basin scale monitoring of carbonate system dynamics and regular socio-surveying of ocean acidification impacts on selected production sectors. The integration of *carbonate chemistry* measurements to assess long term ocean acidification in national monitoring programmes would facilitate coordination survey at the regional level through international and multidisciplinary research activities. Model projections of future ocean acidification in productive regions supporting important fisheries or aquaculture industries will help societies for timely adaptation of fisheries and aquaculture practices.

We recommend building adaptive capacity within the fisheries and aquaculture sectors, especially in the southern Mediterranean basin where dependence on seafood for animal protein source and income is strong. To help achieve this we recommended enhanced multi-stakeholder communication by promoting the exchange of knowledge and building reciprocal trust among the parties (private sector, research institutions, decision makers, producer organisations, regional fisheries management organisation, NGOs). We need to encourage the support of aquaculture practices using species more tolerant to ocean acidification through selective breeding and the development of aquaculture infrastructure that facilitate transport of aquaculture structures, and its mollusks production, between brackish and open sea waters.

Finally, we recommend an integrated economic valuation approach would investigate economic sectors other than fisheries. This would include coastal tourism, which is the most important economic resource for the region and would help put an economic value to the losses that may be incurred by increasing acidification of the Mediterranean and Black Seas. Such an evaluation may be useful in policy decision making about mitigation of and/or adaptation to ocean acidification through a better understanding of the costs/benefits of policy action as well as the costs of policy inaction.

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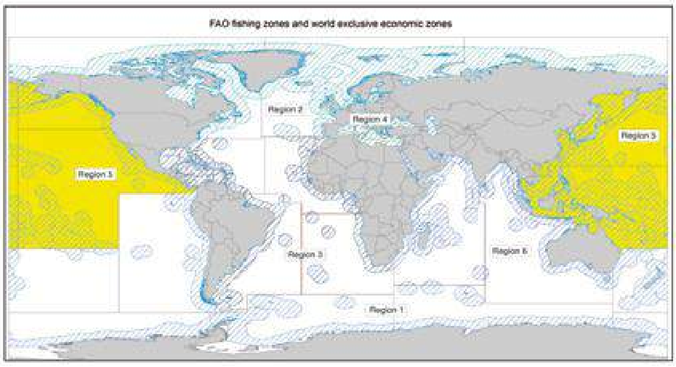
North and Central Pacific Ocean Region

(FAO 61, 67, 71, 77)



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See map in Annex 1, p. 134.

EXECUTIVE SUMMARY

The Pacific Ocean is the largest ocean in the world, with diverse habitats and rich fisheries resources, providing a wide variety of goods and services to human society. Particularly, fisheries and aquaculture are of substantial cultural, nutritional and economic importance to the region. This chapter reviews existing knowledge about the effects of ocean acidification as an additional human-induced driver in affecting marine ecosystems, and the associated goods and services, in the Pacific Ocean, with focuses on habitat forming species, commercially valuable species (fisheries and aquaculture) and ecosystems that are important to the different Pacific sub-regions. Large areas of coral reefs are found in Southeast Asia and South and Central Pacific, calcifying algae as well as cold-water corals in the family Coralliidae found in deep-sea, continental slopes and seamounts in the Pacific which are shown to be highly vulnerable to ocean acidification. In contrast, greater CO_2 concentrations may result in increased productivity, of seagrasses, giant kelp and other non-calcifying seaweed, although particularly life stages of these organisms may be sensitive to more acidic water. Some commercially important molluscs are also shown to be particularly vulnerable to ocean acidification. The sensitivity of molluscs to ocean acidification suggests that some of the greatest socio-economic impacts of increasing CO_2 concentrations will occur in aquaculture industries. The reported impact of increased water acidity on Pacific oyster aquaculture in the Northeast Pacific is provided as a case study. Knowledge on the direct effects on fishes is much more limited. In general, available studies do not show significant effects of ocean acidification on other marine fishes in the Pacific However, synergistic effects from warming and hypoxia may exacerbate the effects of ocean acidification on marine fishes. Also, fishes many be at risk from higher CO_2 concentrations through the indirect effects of ocean acidification on their habitat. Moreover, some of the calcifying organisms that are sensitive to ocean acidification are important food sources for ecosystems in the Pacific Ocean e.g. pteropod molluscs, which may in turn affect their consumers higher up in the food web. As damaging as the effects of ocean acidification and global warming will be for coral reef fisheries, increases in human populations will have the greatest effect on the availability of fish from coral reefs for many years to come. The combined effects of all drivers will be to cause a considerable shortfall between the amount of fish needed by growing populations and the amount that can be harvested sustainably from coral reefs. The projected degradation of coral reefs is also likely to have implications for the tourism sector, which is important in Southeast Asia and the tropical Pacific. To mitigate impacts of ocean acidification on fisheries and aquaculture in the Pacific, the ultimate solution is to reduce and/or capture (if possible) CO_2 emission. However, a range of adaptation measures should be planned and implemented for the currently committed and projected level of ocean acidification to minimize its impacts on fisheries and aquaculture. Better understanding on the effects of ocean acidification a broader range of ecologically and commercially important species is also needed.

1. THE SPECIFICITIES OF THE REGION

The Pacific Ocean is the largest ocean in the world, providing a wide variety of goods and services to human society. It represents almost half of the world's ocean area, bordering the coastline of 50 countries or territories (Figure 1). The wide range of habitats within the Pacific Ocean supports much of the world's marine biodiversity (Cheung and Sumaila in press).

The diverse habitats of the Pacific Ocean range from shallow coasts and islands with coral reefs, estuaries, seagrasses and mangroves to deep slopes and seamounts. Some of these habitats host the highest diversity of marine organisms in the world - the coral triangle (Indonesia, Philippines, Malaysia, Timor Leste, Papua New Guinea and Solomon Islands) is recognized as the center of marine biodiversity. The Pacific Ocean also has the highest species richness of marine species (Cheung *et al.,* 2005).

The rich fisheries resources of the Pacific Ocean provide animal protein and income earning opportunities for coastal communities, and government revenue. The majority of the catch is from continental shelves, although pelagic fisheries resources, such as tuna in the tropical Pacific, also support significant fisheries (Gillett 2009) (Figure 2).

In general, catches from the Pacific increased from ~10 million t in the 1950s, peaked at around 50 million t in the early 1990s and decreased to around 45 million t in the 2000s (Figure 3). Catch in the tropical Pacific increased substantially, driven mainly by expansion of the surface fishery for tuna in Papua New Guinea. For the North and Central Pacific region as a whole, the fisheries of the Northwest Pacific, and particularly China, dominate the total catch. The landed values from the Pacific Ocean increased from ~$US 10 billion in the 1950s to ~$US 50 billion by the 1990s and have remained relatively stable.

Given the diversity of the North and Central Pacific region, we organise the summary further into 4 sub-regions: Northeast Pacific, Northwest Pacific, Southeast Asia, and Tropical Pacific (largely corresponding to FAO fishing areas: 67, 61, 71 and 77).

The major fisheries in the Northeast Pacific include salmon (pink, sockeye, chum, coho and chinook), walleye pollock and Pacific cod. Other commercially valuable species include herring, rockfish, skate, Greenland turbot, sole, plaice, halibut and crab. In addition, the California Current region (an eastern boundary upwelling) has rich pelagic resources, such as Pacific sardine, northern anchovy, jack mackerel, chub mackerel and Pacific herring. In this part of the Pacific, aquaculture has developed mainly along the coast of British Columbia (Canada) and Washington and Oregon States (USA) for Atlantic salmon, oysters and clams.

In the Northwest Pacific, main target species include pollock, Japanese anchovy, mackerel, hairtail, Pacific herring, croakers, squid and a wide variety of tropical species in the southern part of the region. Aquaculture is widely developed in the region, particularly in China and Japan, based on oysters, scal-

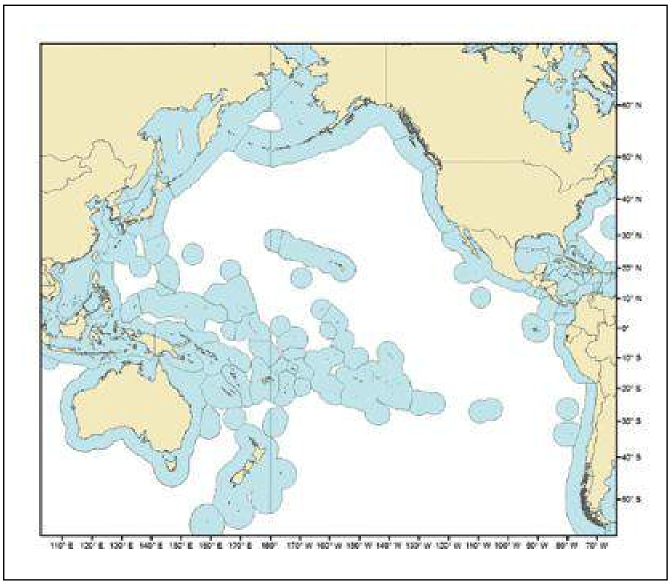

Figure 1.

The Pacific Ocean with boundaries of the exclusive economic zones of countries and territories in the region (blue).

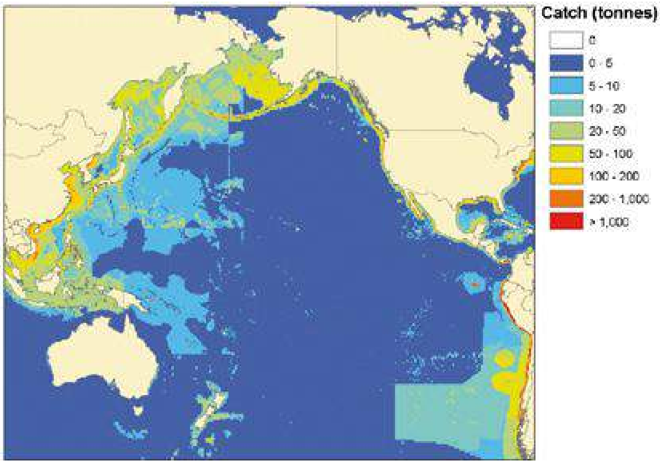

Figure 2.

Estimated annual average fisheries catch from the Pacific Ocean in the 2000s. Derived from an algorithm that allocates fisheries records onto a 30' latitude x 30' longitude grid (see Watson *et al.,* 2004 for details)
(source: Sea Around Us Project).

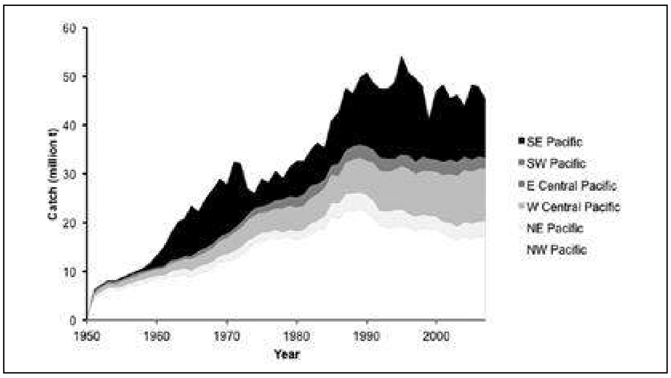

Figure 3.

Time-series of fisheries catches from the Pacific
(source: Sea Around Us Project).

lops, mussels, abalone, seaweeds, groupers and seabreams.

The fisheries and aquaculture operations in the tropical Pacific include oceanic fisheries, coastal fisheries and coastal aquaculture. The oceanic fisheries of the tropical Pacific are dominated by skipjack, yellowfin and bigeye tuna and South Pacific albacore, which together represent >90% of the total catch taken by industrial fleets. The remainder of the catch is comprised predominately of billfish (marlin and swordfish), oceanic sharks and Pacific bluefin tuna (*T. orientalis*) (Lehodey *et al.,* 2010). The coastal fisheries of the region fall into four distinct categories (1) demersal (bottom-dwelling) fish associated mainly with coral reefs, but also with mangroves and seagrasses; (2) near-shore pelagic fish (tuna and other large pelagic fish species that come close to shore); (3) targeted commercial invertebrates (mainly sea cucumbers, trochus, spiny lobsters and crabs); and (4) invertebrates gleaned from the shallow subtidal and intertidal areas of the habitats described above (Pratchett *et al.,* 2011). The main coastal aquaculture enterprises in the region are culturing black pearls in French Polynesia, Cook Islands and Fiji, farming shrimp (mainly in New Caledonia) and growing seaweed in Kiribati, Fiji, Solomon Islands and Papua New Guinea (Bell *et al.,* 2011).

2. SOCIO-ECONOMIC BENEFITS OF FISHERIES AND AQUACULTURE IN EACH SUB-REGION

Fisheries and aquaculture play an important role in the economy and culture of Northeast Pacific countries. For example, in 2011 Alaska's seafood industry generated $US4.7 billion in sales, $US2 billion in income, and over 63,000 jobs, whereas commercial fishermen in the U.S. portion of the California Current landed roughly 544,000 tonnes of finfish and shellfish, earning $710 million in landings revenue. This revenue was dominated by crab ($US182 million) and other shellfish ($162 million) (National Marine Fisheries Service 2012). The estimated total annual revenue from shellfish aquaculture in Washington State alone is $270 million, with shellfish growers directly and indirectly employing more than 3,200 people (Washington State Blue Ribbon Panel on Ocean Acidification 2012).

Fisheries and aquaculture are of substantial cultural, nutritional and economic importance to Northwest Pacific countries. Fish and seafood comprise an important element of national diets in this sub-region. For example, per capita supplies of fish and fish product in Japan are estimated to be approximately 70 kg per year compared to a world average of 16 kg (Schmidt 2003). Fisheries also provide substantial employment. The number of Japanese employed in marine fisheries in 2008 was 221,908 (Japanese Ministry of Agriculture Forestry and Fisheries 2008). Aquaculture production has expanded rapidly in the Northwest Pacific sub-region, particularly in China which accounts for 86% and 67% of aquaculture in the North and Central Pacific region by weight and value respectively. Figure 4 presents the value of aquaculture production for the period 2000-2010 for each sub-region. The Northwest Pacific and China in particular dominate this industry. Figure 5 presents the value of aquaculture production as a percentage of GDP for each sub-region, showing that aquaculture remains a relatively small economic sector even in the Northwest Pacific and Tropical Pacific (accounting for 0.1-0.15% of GDP).

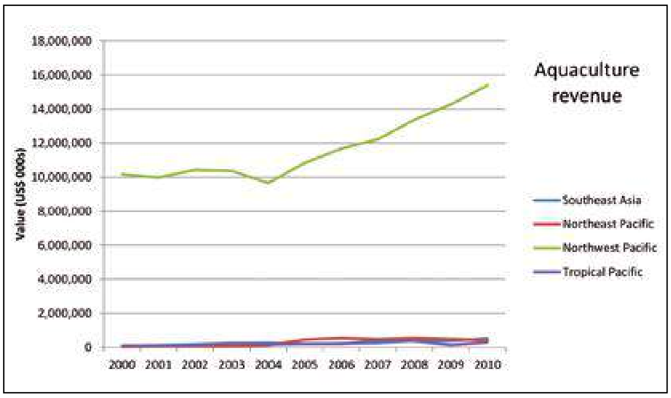

Figure 4.

Aquaculture value (US$ 000s) by sub-region.
Source: FAO 2010 Yearbook.

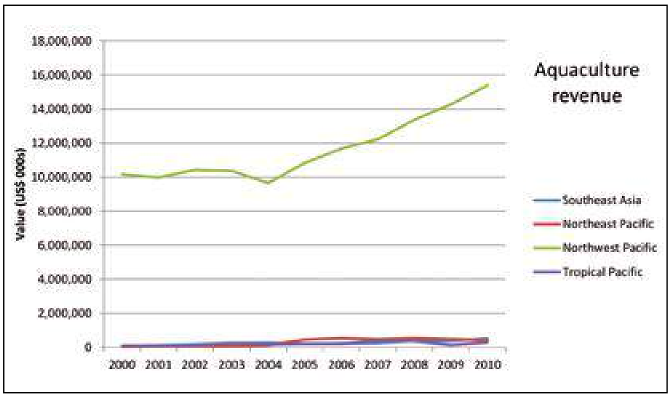

Figure 5.

Aquaculture value as a percentage of GDP by sub-region.
Source: FAO 2010 Yearbook;
World Bank World Development Indicators.

For Southeast Asia, fisheries and aquaculture also do not account for a large share of economic activity. In 2007, the total values of marine fisheries and aquaculture are estimated to be worth approximately US$ 10.5 and US$ 13 billion, respectively (SEAFDEC 2013). These industries are, however, highly important in terms of providing employment and income in coastal areas, and ensuring local food security. In the Philippines, fisheries are estimated to provide approximately half of the dietary protein needs of the population. For lower income groups this dependence on fish is even more pronounced with fish and fish-based products comprising 70% of animal protein for the poor (World Fish Centre 2013).

The major direct financial benefits to economies from fisheries in the tropical Pacific come from contributions to GDP from industrial tuna fishing and onshore processing, and contributions to government revenue from the sale of tuna fishing licenses to distant water fishing nations (DWFNs). Tuna fisheries are also an important source of jobs in the region – more than

12,000 people are employed in tuna canneries or processing facilities, or on tuna fishing vessels (Gillett 2009). Domestic tuna fleets and local tuna canneries or fish processing operations account for between 3% and 25% of GDP in four Pacific Island counties and territories (PICTs) (Gillett 2009). License fees from DWFNs involved in the surface and longline fisheries for tuna now account for between 11% and 63% of government revenue for six of the eight Pacific Island countries that are the Parties to the Nauru Agreement[1].

Fish[2] is an important part of the diet of most people in the tropical Pacific – fish consumption is at least 2–4 times the global average in more than half of all 22 PICTs and fish often makes up 50–90% of dietary animal protein in the rural areas (Bell *et al.,* 2009). Much of this fish comes from coastal fish species associated with coral reefs, mangroves and seagrasses. However, ~30% of the fish consumed consists of large pelagic fish species caught by near-shore small-scale fisheries (Pratchett *et al.,* 2011). Across the region, ~50 % of households in surveyed coastal communities earned their first or second incomes from fishing or selling fish (Pinca *et al.,* 2010).

3. FACTORS AFFECTING FISHERIES AND AQUACULTURE ACROSS THE PACIFIC OCEAN

Overfishing

Evidence suggests that some fisheries in the Northwestern Pacific, Southeast Asia and parts of the tropical Pacific are overfished, whereas fisheries resources in the Northeast Pacific are better managed. For example, in the northern South China Sea, fisheries are under-performing in both ecological and economic objectives (Cheung and Sumaila 2008). Abundance of 12 out of 17 studied taxa declined by over 70% in 15 years over the last four decades (Cheung and Pitcher 2008). Vulnerable fish species such as skates, rays and large-bodied croakers have declined by over 90% during this period (Cheung and Pitcher 2008, Cheung and Sadovy 2004, Sadovy and Cheung 2003). Analysis of catch time-series trends suggest that over 50% of the fish stocks in Southeast Asia are likely to be overfished, leading to an estimated loss of fisheries production of 55-70% (Sumaila *et al.,* 2013). In the tropical Pacific, some coastal fisheries are over-exploited (Pratchett *et al.,* 2011). In contrast, the status of the fisheries resources in the Northeast Pacific appears to be better. Based on a study analysing fish stocks with assessment or survey data, the waters around the U.S.A and Canada in the northeast Pacific are considered “not overfished” and have a “low exploitation rate, with biomass rebuilding from overfishing” (Worm *et al.,* 2009).

Habitat degradation and other drivers

Because of the large population living along the coast of the Pacific Ocean, pollution is a major threat to the health of the marine ecosystems. One of the most important pathways of pollution impact is through nutrient enrichment from the discharge of sewage, agriculture and industrial waste into the ocean, ultimately leading to oxygen depletion. Over 10% of the world’s known eutrophic/hypoxic zones are found in the Pacific (Figure 6). These zones can lead to mortality of marine organisms directly, or indirectly through degradation of their habitat quality and stress-induced increases in disease outbreaks. The main economic consequences include reduced production of fish and shellfish, tourism and ecosystem functions. High shipping volume within the Pacific poses additional ecological risks for the region’s marine ecosystems through pollution and invasive species.

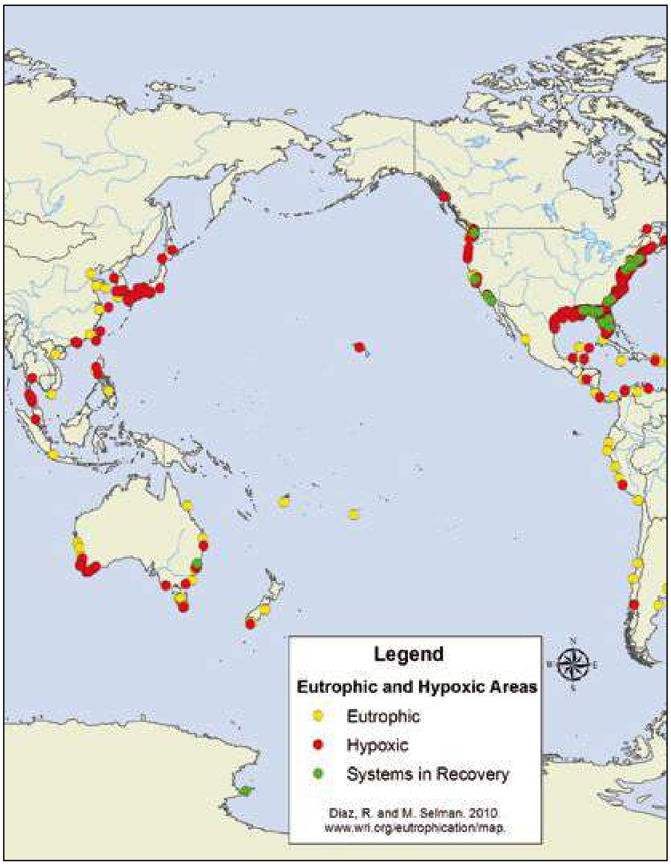

Figure 6.

Area of eutrophic and hypoxic areas in the Pacific
(Diaz and Rosenberg, 2008).

Warming and other changes in ocean conditions

Many regions in the Pacific Ocean have warmed considerably over the last five decades. For example, in the Northeast Pacific, sea surface temperature increased by an average of 0.3 – 0.6 °C from 1982 to 2006 (Belkin 2009) and is projected to increase by 1.0-1.5°C by 2050 relative to 2000 (Overland and Wang 2007). Such changes are likely to affect body size, growth, distributions, phenology and community structure across the food web (Cheung *et al.,* 2013, Pinsky *et al.,* 2013, Poloczanska *et al.,* 2013, Sumaila *et al.,* 2011). Some evidence of shifts in species distribution (mostly poleward or following temperature) and phenology of exploited marine species is

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[1] www.pnatuna.com

[2] Fish is used here in the broad sense to represent both finfish and invertebrates.

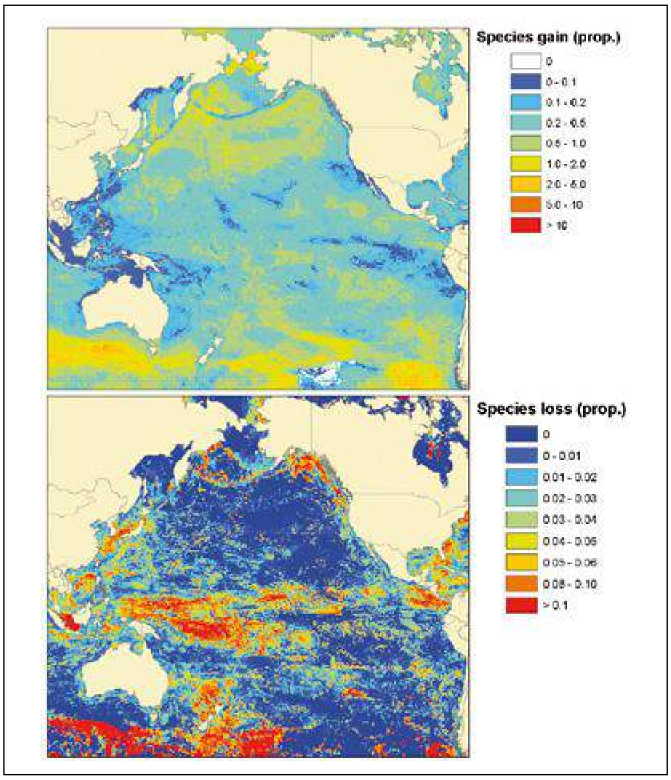

Figure 7.

Projected rate of (a) species gain and (b) loss by 2050 relative to 2005 (10-year average) under the SRES A1B scenario
(redrawn from Cheung *et al.,* 2009).

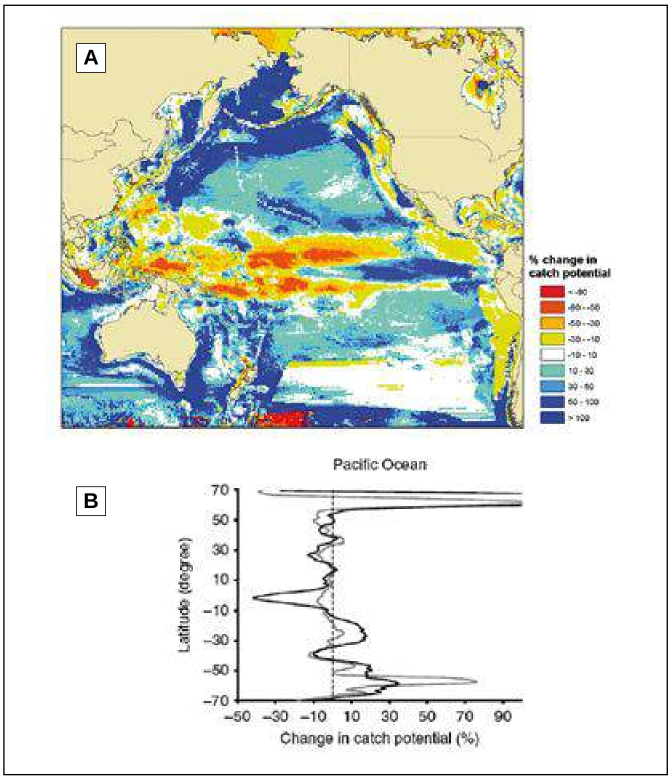

Figure 8.

Projected changes in maximum catch potential by 2055 relative to 2005 (10-year average) in Pacific Ocean:
(a) map of changes in maximum catch potential under the SRES A1B scenario and (b) latitudinal zonal average changes under SRES A1B (black) and B2 (grey) scenarios
(redrawn from Cheung *et al.,* 2010).

available in the Pacific (Pinsky *et al.,* 2013) , potentially leading to the increased dominance of warmer water species in fisheries catches from the 1970s to the 2000s (Cheung *et al.,* 2013).

Distributions of marine species in the Pacific Ocean are projected to continue to shift in the coming decades, leading to species invasions and local extinctions (Cheung *et al.,* 2009) (Figure 7). Spawning habitat of bigeye tuna (*Thunnus obesus*) in the Pacific Ocean is projected to improve in the subtropical Pacific, while both spawning and feeding habitats improve in the eastern tropical Pacific regions (Lehodey *et al.,* 2010). In contrast, the Western Central Pacific becomes less favourable for spawning of bigeye tuna.

Primary production is expected to change under climate change in the Pacific Ocean. Specifically, the subtropical biome in the North Pacific is projected to expand by ~30% by 2100 relative to 2000 under the SRES A2 scenario, with a contraction of the temperate and equatorial upwelling biomes of 34% and 28%, respectively (Polovina *et al.,* 2011). Simultaneously, primary production is projected to increase by 26% in the subtropical biome and decrease by 38% and 15% in the temperate and equatorial biomes, respectively (Polovina *et al.,* 2011). Dominant phytoplankton groups are projected to shift from diatoms to other smaller phytoplankton, with annually averaged percentage of diatoms decreasing by up to 18% in the subtropical region and 6% in the subarctic region (Hashioka and Yamanaka 2007). The changes in species distribution and primary production are expected to alter potential fisheries catch in the Pacific (Cheung *et al.,* 2011; Cheung *et al.,* 2010) (Figure 8).

4. OCEAN ACIDIFICATION AND ITS POTENTIAL EFFECTS ON ECOSYSTEMS IN THE PACIFIC

Increases in atmospheric carbon dioxide (CO_2) are projected to lead to substantial additional acidification of the ocean, reducing the average pH of the ocean by 0.2–0.3 units under the B1 and A2 scenarios (similar to RCP 6.0 and 8.5) by 2100. In particular, aragonite saturation levels in the tropical Pacific Ocean are expected to fall below 3.5 under A2 by 2035 and decrease to 2.4 under A2 in 2100 (Ganachaud *et al.,* 2011). The average depth of the aragonite saturation horizon in the region has been 300 m at 8°N, and deeper to the south and to the north. This horizon is projected to become shallower over time, reaching 150 m in 2100 under the A2 scenario (Ganachaud *et al.,* 2011).

The effects of ocean acidification and decreasing aragonite saturation levels on the ecosystems supporting fisheries and aquaculture across the north and central Pacific are set out below. The section is subdivided into habitat forming species, commercially valuable species (fisheries and aquaculture) and ecosystems that are important to the Pacific sub-regions.

4.1. Habitat forming species

Corals

Large areas of coral reefs are found in Southeast Asia and South and Central Pacific, providing essential habitats for marine organisms and ecosystems. Due to the importance of carbonate ions for reef calcification (Doney *et al.,* 2009, Hoegh-Guldberg 1999, Hoegh-Guldberg *et al.,* 2007), reductions in aragonite saturation will decrease the calcification rate of reef-building corals and other calcifying organisms. Tipping the balance between calcification and erosion of reefs in favour of erosion will result in a progressive loss of reef structure and integrity over time. The precise relationship between reef calcification and erosion, however, depends on a number of factors such as water quality, location and latitude (Hoegh-Guldberg *et al.,* 2011).

As well as declining calcification rates, reduced carbonate ion concentrations are likely to increase the rate of biological erosion (via reduced density of coral skeletons and increased dissolution), allowing the activities of external bio-eroders (e.g. fish and sea urchins) as well as internal bio-eroders (e.g. worms and sponges) to dominate (Hoegh-Guldberg *et al.,* 2011).

Even under good management (e.g. controlling runoff), coral cover is expected to decrease from the present-day maximum of 40% to 15–30% by 2035 and 10–20% by 2050 due to the combined effects of ocean acidification and higher sea surface temperatures (Hoegh-Guldberg *et al.,* 2011), matching the rate of decline over the past 30 years (Bruno and Selig 2007). By 2100, live coral cover is expected to be reduced by >90%. The evidence that the coral reefs of the future will bear limited resemblance to present-day reefs is mounting (Fabricius *et al.,* 2011, Hoegh-Guldberg *et al.,* 2011).

The long-lived (>200 years) and slow-growing (radial growth rate of 0.24 to 0.62 mm/year) precious corals in the family Coralliidae (*Table 1*) found in deep sea, continental slopes and seamounts in the Pacific (Nozomu & Tomohiko 2010) are also expected to be affected by ocean acidification. Among 31 species described to date, the axial skeletons of seven species are used in Jewelry.

The rate of calcification of such corals will significantly decrease by the end of this century due to effects on spicule morphology, metabolism and feeding activity (Bramanti *et al.,* 2013, Cerrano *et al.,* 2013). Due to the sensitivity of the deep-sea environment to ocean acidification (Turley *et al.,* 2007), there is also a risk that some populations of precious coral will be extinct by 2100.

Mangroves

Extensive mangroves are found in Southeast Asia and the tropical Pacific, providing important ecological functions and ecosystem services. Even if soil acidity increases, mangroves are not expected to be affected adversely because many mangrove soils are neutral to slightly acidic due to sulphur-reducing bacteria and the presence of acidic clay (Waycott *et al.,* 2011).

Seagrasses

Extensive seagrass habitats occur in the tropical Pacific and Southeast Asia. Seagrasses are not expected to be vulnerable to increasing concentrations of CO_2 in seawater. Instead, greater CO_2 concentrations may result in increased productivity, biomass and reproductive output of seagrasses (e.g. Palacios & Zimmerman 2007). The photosynthetic rates of seagrasses are currently limited by the availability of CO_2 - higher concentrations of CO_2 at lower pH will result in faster photosynthetic rates (Invers *et al.,* 2001, Waycott *et al.,* 2011). However, potential synergistic effects between ocean acidification and other oceanographic changes such as warming are unknown.

Giant kelp and other seaweed

The giant kelp *Macrocystis pyrifera* provides important habitats for coastal marine ecosystems along the coast of northern and southern Pacific Ocean. Like seagrasses, the macroscopic

Table 1.

List of precious corals in North & Central Pacific (modified from Liverino and Johnson, 1989).

Species	English name	Trade name	Distribution	Depth range (m)
Paracorallium japonicum	Japanese red coral	Moro, Aka-sango)	Japan, Taiwan	100 - 300
Corallium elatius	Pink coral	Cerasuolo, Momoiro-sango, Satsuma	Japan, North South China Sea	100 - 400
Corallium konojoi	White coral	Bianco, Shiro-sango	Japan, North South China Sea	76 - 276
Corallium sp.	Deep-sea coral		Midway	900 - 1500
Corallium laauense (= *C. regale*)	Pink coral		Hawaii	350 - 600
Corallium secundum	Pink coral, Angel skin	Midway, Rosato	Hawaii, Midway	350 - 475

stage of kelp may benefit from more CO_2 through enhanced photosynthetic rates. However, effects of ocean acidification on germination of kelp are variable (e.g., positive effect of increasing CO_2, but negative effect of decreasing pH) (Roleda *et al.,* 2012). Other non-calcifying seaweeds are also likely to benefit from increasing global CO_2 concentrations in general (Kroeker *et al.,* 2013), partly by reducing the energetic costs of capturing carbon for photosynthesis (Cornwall *et al.,* 2012). Studies on commercially important North Pacific seaweed species are rare but a few early publications on *Porphyra* spp. (cultured in China, Japan and Korea and used in sushi) indicate increased photosynthesis and growth rates of *Porphyra yezoensis* (Gao *et al.,* 1991) and *Porphyra haitanensis* (Zou & Gao 2002) when exposed to elevated CO_2

In contrast, ocean acidification may reduce growth of calcifying algae, by increasing the cost of calcification and the likelihood of dissolution (Harley *et al.,* 2012). Experiments have shown that acidification is consistently related to reduced growth rates in calcified macroalgae, although there are considerable variations in the level of responses between species (Kroeker *et al.,* 2010).

Like seagrass, the potential synergistic effects between ocean acidification and other oceanographic changes such as warming on seaweed taxa are unclear.

4.2. Other commercially important species

Sea cucumbers

There has been no research on the effects of projected ocean acidification on the only species of sea cucumber cultured in the tropical Pacific (sandfish, *Holothuria scabra*). However, research on other sea cucumbers, and related sea urchins (Brennand *et al.,* 2010, Byrne 2011, Byrne *et al.,* 2011), suggests that sandfish may have some sensitivity to reduced concentrations of carbonate ions in sea water. Larval survival may be affected and the size and strength of the calcareous spicules in the outer layer of their skin is likely to be reduced as acidification of the ocean increases (Pickering *et al.,* 2011).

Pacific oyster

Pacific oysters, *Crassostrea gigas*, are negatively affected by decreased aragonite saturation state. In a coastal oyster hatchery in Oregon, U.S.A., where intake waters experienced variable carbonate chemistry (aragonite saturation state, 0.8 to 3.2; pH, 7.6 to 8.2), larval production and mid-stage growth were significantly negatively correlated with the aragonite saturation state of waters in which larval oysters were spawned and reared for the first 48 h of life (Barton *et al.,* 2012).

Pearl oysters

Despite the value of pearl farming to the tropical Pacific (Pickering *et al.,* 2011), there has been limited research on the effects of ocean acidification on the production of pearls from the black-lipped pearl oyster *Pinctada margaritifera* . However, research on the closely-related *Pinctada fucata* (Welladsen *et al.,* 2010) suggests that survival and growth of wild *P. margaritifera* spat, which provide most of the oysters for pearl farms in the tropical Pacific, are expected to decrease as shells are weakened by lower aragonite concentrations. Reduced availability of aragonite is also expected to affect pearl quality because aragonite is a key component of nacre (Pickering *et al.,* 2011).

Other bivalves

The scallop and mussel fisheries and aquaculture operations in the Northwest Pacific, mainly in China and Japan, which account for about 90% of global production, are vulnerable to ocean acidification. Ocean acidification affects scallops and mussels negatively through reduced calcification, growth and survival (Kroeker *et al.,* 2013).

Shrimp

Like some other crustaceans, penaeid shrimp typically exert high biological control over calcification by gradually accumulating intracellular stocks of carbonate ions to harden their chitin and protein exoskeletons, usually in the less soluble form of calcite. Therefore, formation of the exoskeleton in shrimp is not highly sensitive to the projected reductions in aragonite saturation expected to result from ocean acidification. However, the species of shrimp farmed in New Caledonia, *Litopenaeus stylirostris,* may be more sensitive to acidification of sea water than other species of penaeid shrimp because of its thinner exoskeleton (Pickering *et al.,* 2011). Given the detrimental effects of marks such as ‘black spot’ on the price received for shrimp by farmers in New Caledonia, any deformities due to the effects of ocean acidification on the thinner exoskeleton of the species would be expected to reduce profits.

Tuna

Little research has been done of the effects of ocean acidification on the four main species of tuna (skipjack, yellowfin, bigeye and South Pacific albacore) that support major fisheries in the tropical Pacific. However, experiments have begun on yellowfin tuna to investigate the effects of lower pH on sperm vitality, egg fertilization, egg and larval development, where genotype has an effect on response of eggs and larvae to ocean acidification (Scholey *et al.,* 2012) .

Tuna could be directly sensitive to the projected changes in pH in at least two other ways. Firstly, an increase in carbonic acid from more acidic seawater could lead to a narrowing of the optimal thermal performance window and, consequently, altered resistance, metabolic rate and behaviour of tuna (Pörtner and Farrell 2008). In particular, the additional energy required to compensate for acidosis could lead to lower rates of growth and egg production. Secondly, the growth and formation of the ear bones (otoliths) of tuna may be susceptible to lower pH because they are composed of aragonite. If so, the effects could be significant because otoliths are important for orientation and hearing, especially during the larval stage of fishes (Munday *et al.,* 2009).

The changes in the availability of species of calcifying phytoplankton and zooplankton within the lower trophic levels of the food web in response to ocean acidification mentioned above may have indirect effects on the distribution and abundance of tuna in the tropical Pacific. However, such effects may be relatively minor because calcifying organisms represent a minor component of the food web supporting tuna (Le Borgne *et al.,* 2011) (see below) and tuna are opportunistic predators.

Coral reef fishes

CO_2 concentrations of up to 1000 ppm do not appear to affect the growth or development of larvae of tropical Pacific coral reef fish but more research is needed to test the effect of elevated CO_2 on the early life stages across a broader range of species, and to examine possible synergistic effects of elevated temperature and CO_2.

A greater concern is the effect that elevated CO_2 levels have on the sensory ability of larval fish. Larvae from the limited number of coral reef fish species that have been tested so far lose their ability to distinguish olfactory cues from their preferred settlement habitat, or to detect and avoid the smell of predators, at the end of their larval phase when exposed to CO_2-acidified water (Devine *et al.,* 2012, Dixson *et al.,* 2010, Ferrari *et al.,* 2011, Munday *et al.,* 2009). The larvae of many marine fish use chemical cues for finding their way to suitable settlement habitat (Gerlach *et al.,* 2007), so any effects of ocean acidification on this process could have serious implications for the replenishment of adult populations (Munday *et al.,* 2010). There has been negligible change in ocean pH over the past 800,000 years (Lüthi *et al.,* 2008) and most tropical marine fish are expected to lack the genetic variation necessary for rapid adaptation to changes in seawater chemistry.

The other way that coral reef fish are at risk from higher CO_2 concentrations is through the indirect effects of ocean acidification on their habitat. The loss of live coral cover and structural complexity of reefs as pH decreases, and SST increases, is expected toreduce the number of fish species associated with reefs, and eventually the productivity of coral reef fisheries. Under the A2 emissions scenario, catches of reef fish are projected to decline by 20% by 2050, and by up to 50% by 2100 (Pratchett *et al.,* 2011).

Other finfish

In general, available studies do not show significant effects of ocean acidification on other marine fishes in the Pacific (Kroeker *et al.,* 2013). For example, Pollock seems to be resilient to projected ocean acidification levels in the Bering Sea and Gulf of Alaska for 2100 (Hurst *et al.,* 2012). However, synergistic effects from warming and hypoxia may exacerbate the effects of ocean acidification on marine fishes (Pörtner 2010).

5. EFFECTS ON FOOD WEBS

Some of the calcifying organisms that are sensitive to ocean acidification are important food sources for ecosystems in the Pacific Ocean e.g. pteropod molluscs. These organisms will need to expend more energy for calcification as the aragonite saturation horizon becomes shallower, and super-saturation levels in the surface waters decrease (Le Borgne *et al.,* 2011). Other organisms, such as coccolithophorids (haptophytes) in the phytoplankton, and foraminiferans and non-pteropod molluscs in the zooplankton, have shells made of calcite. They are expected to be less sensitive because greater decreases in pH are needed for ‘shoaling’ of the calcite saturation horizon (Orr *et al.,* 2005). Thus, acidification may have an indirect effect on the species composition of phytoplankton and other low trophic level organisms (Le Borgne *et al.,* 2011), which may in turn affect their consumers higher up in the food web.

Although ocean acidification could have unpredictable and cascading effects on food webs, the calcareous organisms likely to be affected directly are a minor part of the ecosystem in the tropical Pacific. Even in the relatively nutrient-rich Pacific equatorial upwelling area, for example, calcareous organisms represent only 1–5% of the phytoplankton, ~6 of microzooplankton and mesozooplankton and ~2% of the micronekton (Le Borgne *et al.,* 2011).

6. SOCIO-ECONOMIC IMPACTS

Mollusc fisheries

The sensitivity of molluscs to ocean acidification (Kroeker *et al.,* 2013) suggests that some of the greatest socio-economic impacts of increasing CO_2 concentrations will occur in aquaculture industries. Cooley and Doney (2009) estimate the impact of ocean acidification on gross revenues for US mollusc fisheries up to 2060. They combine information from experiments on the impact of ocean acidification on growth rates of mollusc with data on US fisheries harvests and prices. Baseline future revenues are projected to 2060 assuming no changes in ecological and economic conditions prevailing in 2007 (i.e., catch, prices and revenues remain constant). Under an ocean acidification scenario, the time profile of increasing impacts on mollusc growth is assumed to be linear and proportionately related to revenue for the period 2007-2060. The estimated present value of losses in revenue are shown to be sensitive to CO_2 emission trajectories, impacts on mollusc growth and the discount rated used in calculating present values. Under the IPCC A1F1 scenario, the present value of lost revenue is estimated to be US$ 2,557 million (25% reduction in mollusc growth at 740 ppm CO_2; 2% discount rate).

Moore (2011) uses an integrated biogeochemical-economic model to estimate the potential impacts of ocean acidification on the US market for oysters, scallops, clams, and mussels for the period 2010-2100. The welfare measure that is estimated is the compensating variation of US households. Compensating variation reflects the change in consumer welfare following a change in prices and is defined as the amount of additional income that a household would need in order to obtain their original level of utility prior to a price increase. The estimated impact therefore represents the loss in consumer welfare due to increased mollusc prices caused by ocean acidification. The change in mollusc prices is modelled using a Cobb-Douglas production function with environmental quality as an input. Changes in household consumption of molluscs and alternative meats with respect to income and food prices is modelled using a two-stage demand system to estimate the parameters of a representative household's expenditure function. The estimated expenditure function is then used to calculate the additional income that a representative household would require to obtain their utility level under a "medium" ocean acidification scenario (Representative Concentration Pathways RCP8.5) versus a "high" ocean acidification scenario (RCP6). The present value of aggregated reduced consumer welfare is estimated to be US$ 735 million for the period 2010-2100 using a discount rate of 5%. The most tenuous link in the integrated model is the relationship between changes in mollusc growth rates and prices. The Cobb-Douglas production function that is used is an assumed relationship (unitary price elasticity with respect to mollusk growth rates) rather than being empirically determined.

Narita *et al.,* (2012) estimate the value of global and regional loss of mollusc production due to ocean acidification over the period 2000-2100. A partial-equilibrium analysis is used to quantify both producer and consumer surplus and accounts for two determinants of welfare change, namely reduced production/consumption and increased prices. Following Cooley and Doney (2009), the rate of shellfish harvest loss is assumed to be equal to the decrease in calcification rate due to ocean acidification. Narita et al (2012) use an estimate of the decrease in calcification rate from a different meta-study (Kroeker *et al.,* 2010), which is higher than that used by Cooley and Doney (2009). The results show that the annual global costs in 2100 could be over 100 billion US$ under a business-as-usual emission trend and assuming that demand for mollusks increases with income, the trend for which is based on the IPCC projections. The major determinants of this cost estimate are the impacts on Chinese production, which is projected to dominate global production, and the expected increase in demand for molluscs in developing countries, including China, in accordance with future income rise. The analysis also indicates that in key regions such as China and the USA, the economic losses are roughly evenly divided between producers and consumers, with slightly greater relative consumer losses for China as a result of relatively inelastic demand of mollusks in that country.

Tuna fisheries

The impacts of ocean acidification on the substantial tuna fisheries in the tropical Pacific (Table 2) cannot be assessed at the present time. In any event, they will need to be considered in the context of the projected effects of global warming on the contributions of the dominant tuna species in the region to the economies of PICTs (Bell *et al.,* 2013, Bell *et al.,* 2011, Lehodey *et al.,* 2011). Any changes to the catches of tuna due to ocean acidification are expected to have socio-economic implications across the region, affecting government revenue and GDP in PICTs where tuna are caught and/or processed.

Table 2:

Total catch and estimated landed value of the four species of tuna, and main fishing methods, for the Western and Central Pacific Ocean (WCPO) Convention area in 2009
(source: Secretariat of the Pacific Community,
Oceanic Fisheries Programme).

Species of tuna	Catch (tonnes)	Value (USD)
Skipjack	1,789,979	2,193,000
Yellowfin	433,788	1,023,000
Bigeye	118,657	650,000
Albacore	125,479	320,000
Total	**2,467,903**	**4,186,000**
Fishing method	**Catch (tonnes)**	**Value (USD)**
Purse-seine	1,894,500	2,354,000
Longline	223,792	1,296,000
Pole and line	165,814	344,000
Other	183,797	192,000
Total	**2,467,903**	**4,186,000**

Coral reef fisheries and tourism

As damaging as the effects of ocean acidification and global warming will be for coral reef fisheries, increases in human populations will have the greatest effect on the availability of fish from coral reefs per capita in several PICTs for many years to come (Bell *et al.,* 2011). The combined effects of all drivers will be to cause a considerable shortfall between the amount of fish needed by growing populations (Bell *et al.,* 2009, Rice and Garcia 2011) and the amount that can be harvested sustainably from coral reefs (Bell *et al.,* 2011).

Brander and Eppink (2012) examine the impact of multiple stressors, including ocean acidification, on the value of coral reef related fisheries in Southeast Asia. The study estimates the forgone value of reef related fisheries due to loss of coral reefs under a "business-as-usual" scenario of increasing threats over the period 2000-2050. The scenario describing loss of coral reef is based on the results of the Reefs at Risk Revisited assessment (Burke and SpaLding 2011). For Southeast Asia as a whole, the annual loss in value of reef related fisheries is approximately US$ 6 billion in 2050 (95% prediction interval of US$ 5.15 – 6.13 billion). The present value of the impact on fisheries for the period 2000-2050 is estimated to be approximately US$ 57.98 billion. These losses are suffered largely by Indonesia and the Philippines.

The projected degradation of coral reefs is also likely to have implications for the tourism sector, which is important in Southeast Asia and the tropical Pacific. A key challenge will be finding ways to maintain the attractiveness of coral reefs as the frequency of coral bleaching events increases and net erosion of reefs occurs due to the effects of ocean acidification (Hoegh-Guldberg 2011, Hoegh-Guldberg *et al.,* 2011).

7. POLICY AND ADAPTATION PLANNING

To mitigate impacts of ocean acidification on fisheries and aquaculture in the Pacific, the ultimate solution is to reduce and/or capture (if possible) CO_2 emissions. However, a range of research and adaptation measures should be planned and implemented for the currently committed and projected level of ocean acidification to minimize its impacts on fisheries and aquaculture. Principles of these adaptation measures include:

- Continuing to implement ecosystem-based management and integrated coastal zone management to increase the resilience of marine ecosystems, with fine-tuning focus on ocean acidification – measures that have clear co-benefits;
- Adjusting stock recovery/restoration plans and conservation measures to adapt to potential effects of ocean acidification;
- Assessing potential risk of ocean acidification on future fish stocks in multi-lateral negotiations for catch sharing (e.g., for tropical Pacific tuna);
- Increasing communication between academia, industry and national/international agencies about the impacts of ocean acidification and practical adaptation strategies.
- Assess vulnerability of key fish and invertebrate species providing food and livelihood to the direct and indirect effects of OA .
- Monitor carbonate chemistry and its impacts on habitats supporting key fish species.

More specific adaptation measures that are suggested for fisheries and aquaculture are discussed below.

Fisheries

Plans are needed to provide access to the fish required for economic benefits, livelihood and food security in the face of growing populations, climate change and ocean acidification. Here, we focus our discussion on tropical Pacific fisheries that range from large-scale industrial fishing (tuna fisheries) to small-scale subsistence coastal fisheries.

In general, adaptation plans for ocean acidification in the tropical Pacific involve (1) improving the management of coastal habitats and fish stocks to reduce the gap to be filled between the fish needed for food security and sustainable fish harvests from coral reefs; (2) assessing how best to fill the gap with tuna; (3) promoting the 'vehicles' needed to deliver the tuna required; and (4) allocating the appropriate proportion of the tuna catch to meet the needs for food security (Bell *et al.,* 2009; Bell *et al.,* 2011).

Specifically, a number of adaptation options to retain the economic benefits flowing to PICTs from tuna and coastal fisheries as global warming and CO_2 emissions increase have been suggested (Bell *et al.,* 2011, 2013b). Examples of these adaptation options include:

- Full implementation of the regional fishing effort schemes that incorporate the effects of climate variability and climate change, for example, the 'vessel day scheme' operated by the Parties to the Nauru Agreement.
- Diversify sources of fish for canneries and maintain trade preferences, e.g. an Economic Partnership Agreement with the European Union.
- Continued conservation and management measures for all species of tuna to maintain stocks at healthy levels and make these valuable species more resilient to climate change.
- Energy efficiency programmes to assist fleets to cope with oil price rises, minimise CO_2 emissions, and reduce costs of fishing further afield as tuna move east due to the effects of global warming on the tropical Pacific Ocean (Lehodey 2011, Ganachaud *et al.,* 2011).
- Pan-Pacific tuna management through a merger of the Western and Central Pacific Fisheries Commission (WCPFC) and Inter-American Tropical Tuna Commission to co-ordinate management measures across the entire tropical Pacific.
- Manage catchment vegetation to reduce transfer of sediments and nutrients to rivers and coasts to reduce damage to coral reefs.
- Foster the care of coral reefs by preventing pollution, managing waste and eliminating direct damage to these habitats.
- Sustain and diversify catches of coral reef fish to maintain the replenishment potential of all stocks.
- Install fish aggregating devices (FADs) (SPC 2012) close to the coast to improve access to tuna and other large pelagic fish for rural communities as human populations increase and coral reef fish decline.
- Develop coastal fisheries for small pelagic fish species, e.g. mackerel, anchovies, pilchards, sardines and scads.
- Improve simple post-harvest methods, such as traditional smoking, salting and drying, to extend the shelf life of fish when good catches of large or small pelagic fish are made.
- Develop hatchery and grow-out systems for expansion of semi-intensive and intensive freshwater pond aquaculture.

Clearly, effort of small-scale fishers will need to be increasingly transferred from fish associated with coral reefs to tuna and other large oceanic fish when they come close to the shore. Transferring effort to oceanic fish species is not only expected to help maintain fish supplies for growing populations as the projected declines in coral reef fish occur (Pratchett *et al.,* 2011), it should also create additional income earning opportunities in the central and eastern Pacific due to projected changes in the distribution of tuna (Lehodey *et al.,* 2011).

Adapting coral reef fisheries to the effects of ocean acidification must be considered in the context of the many other drivers expected to affect the ability of these fisheries to maintain their primary socio-economic contribution – providing fish for the food security of coastal communities. The other major drivers affecting the availability of fish from coral reefs are population growth (Bell *et al.,* 2009) and increases in SST and the severity of tropical cyclones (Hoegh-Guldberg *et al.,* Pratchett *et al.,* 2011).

Aquaculture

Despite the potential severity of impacts of ocean acidification on mollusc culture, a number of adaptations options are available. These include:

- Improved real-time monitoring of intake-water pH, pCO_2, salinity, temperature, and dissolved oxygen at shellfish hatcheries. This knowledge enables hatchery operators to draw water at times and from areas with lower CO_2 and higher pH (Washington State Blue Ribbon Panel on Ocean Acidification 2012).
- Construction of new shellfish hatcheries in areas less susceptible to ocean acidification. One Washington state oyster farmer constructed a new *C. gigas* hatchery in Hawaii at a cost of approximately $1M. Larvae are shipped from Hawaii to Washington State for grow-out (Welsh 2012).
- Introducing new species that are more resilient to ocean acidification. This needs much more research on ecological impacts and feasibility.
- Selective breeding of molluscs for resistance to reduced pH (Parker *et al.,* 2011).
- Polyculture of seaweed and molluscs to reduce local concentrations of CO_2 to acceptable levels.

Case study : Oyster farming in Northeast Pacific

The U.S. west coast shellfish industry provides one of the clearest existing case studies of the effects of ocean acidification on marine resources and the resulting economic impacts. Between 2005 and 2009, several commercial oyster hatcheries in Washington state and Oregon experienced almost complete failure of larval *Crossostrea gigas* production. Production of wild oyster larvae in the region was also very poor. The natural and hatchery production failures were linked directly to ocean acidification (Barton *et al.,* 2012), which is anticipated to worsen in the Northeast Pacific in the future (Gruber *et al.,* 2012).

Shellfish aquaculture is an important economic activity in the U.S. Pacific Northwest. Annual sales of shellfish grown in Washington State exceed $107 million. Oysters comprise over 80 percent of the state's farmed shellfish harvest and more than 50 percent of its total annual sales ($58 million) (Washington State Blue Ribbon Panel on Ocean Acidification 2012). Ocean acidification will have a significant negative effect on the industry.

The shellfish aquaculture industry is actively adapting to the threat of ocean acidification. Hatcheries now monitor seawater carbonate chemistry to optimize the timing of seawater intake. Hatcheries have been constructed in locations less susceptible to ocean acidification. Research is also being conducted to identify shellfish aquaculture species that may be more robust to the effects of ocean acidification. None of these actions, however, will mitigate the effects of ocean acidification on wild shellfish stocks.

8. RESEARCH REQUIRED

Although current evidence does not suggest significant effects of ocean acidification on finfish, the high importance of finfish fisheries in the Pacific warrants better understanding of direct and indirect effects of ocean acidification on fish stocks. Given the great economic importance of tuna fisheries to government revenue and GDP in the tropical Pacific, and the fact that tuna will have to supply much of the additional fish needed for food security in the region as human populations grow (Bell *et al.,* 2011, 2013b), research on the effects of ocean acidification on tuna is a priority. The preliminary research on yellowfin tuna (Scholey *et al.,* 2012) needs to be expanded and comparable research is needed on the species that is the mainstay of the pursed-seine fishery – skipjack tuna (Lehodey *et al.,* 2011) (Table 2). Also, managers are already expecting to have to switch fishing effort from coral reef-associated fish species to tuna to provide the fish required for growing populations (as indicated above). Gaining a better understanding of the likely effects of ocean acidification on replenishment of reef fish populations will assist the effective planning of this important adaptation.

A better understanding of the effects of ocean acidification on important shellfish aquaculture operations, such as those in Southeast Asia and tropical Pacific, is needed. For example, the pearl industry in the tropical Pacific is already suffering from over-supply of pearls and competition from freshwater pearls. Less efficient operations due to ocean acidification, especially difficulties in producing pearls of high quality, can be expected to exacerbate the problems. Research is needed urgently to identify whether sites for growing pearls can be located where the adverse effects of both higher water temperatures and lower pH on nacre formation can be reduced. Selective breeding programs, similar to those underway for rock oysters elsewhere in the Pacific (Parker *et al.,* 2011), are needed to determine whether such programmes may be a viable option for maintaining pearl quality as pH decreases.

For the shrimp and other crustacean fisheries and aquaculture, research is required to determine if there will be any adverse effects of ocean acidification on the exoskeleton of shrimps (e.g., *Litopenaeus stylirostris* the most widely farmed shrimp in the tropical Pacific region). There are already problems marketing this species internationally due to competition from other countries at the top end of the market and any effects of lower pH on product quality can be expected to make marketing even more difficult.

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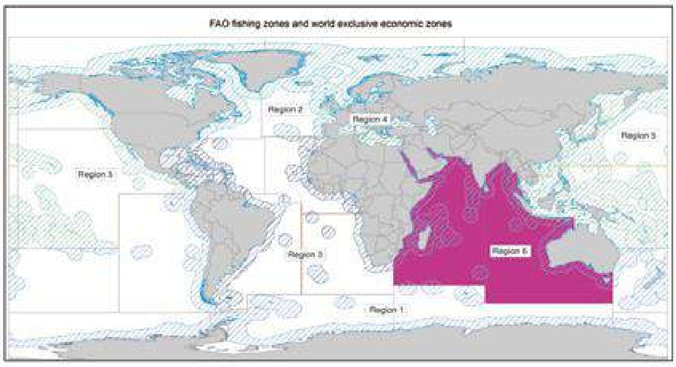
Indian Ocean and Red Sea

(FAO 51, 57)



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See map in Annex 1, p. 135.

EXECUTIVE SUMMARY

The Indian Ocean stretches 10,000 km east to west, and is bordered by the land masses of Indo-Australia, Asia and Africa. The region, from 20 N to 60 S latitude, covers an area over 73 million km^2 including the Red Sea and the Persian Gulf. The zone north of the equator is characterized by seasonal monsoons, which are tied closely to the trade winds, the Indian Ocean Dipole, and the Pacific Ocean El Niño Southern Oscillation via the Indonesian Throughflow. The major year-round current of the Indian Ocean is the westward-flowing South Equatorial Current located from 15-20 degrees South latitude. Deep water circulation is controlled primarily by inflows from the Atlantic Ocean, the Red Sea, and Antarctic currents

Physical and biological scientific data related to ocean acidification for the Indian Ocean is lacking; therefore, inferences using data from similar ecosystems of other regions have been made. Much of this review is focused on a more studied portion of the region, the Western Indian Ocean (WIO), which lies within FAO statistical area 51 and comprises ten countries: Somalia, Kenya, Tanzania, Mozambique, South Africa, Madagascar, Comoros, Seychelles, Mauritius and the dependent Rodrigues, and the French dependent territory of La Réunion. The marine ecosystems of the WIO are typified by coral reefs, extensive mangrove forests and seagrass beds, granitic and volcanic oceanic islands and atolls. The diverse array of coastal resources in the WIO provides for key livelihood activities including fisheries and tourism, aquaculture, shipping, and mineral exploitation. There are marked differences between countries in terms of development and fisheries: the highest dependence on fisheries is found in Quirimbas, northern Mozambique and Andavadoaka, Madagascar, with over 80% of households in each of these areas dependent on marine resources for food and income.

The marine environmental stressors for this area are many and have local, regional and global sources, but a primary pressure on ecosystem resources is the large human population. The impacts of increased human activity and use of coastal marine resources in the region is evident from decreasing fish catches, increasing destructive fishing practices and increasing volume of untreated sewage and nutrient runoff released into near-shore areas. The human population around the whole Indian Ocean exceeds 2.5 billion, more than 1/3 of the world population. Given current population growth rates, that population can be projected to exceed 5 billion by the year 2050. Ocean acidification is one of a suite of factors that contribute to the decline of marine resources in the region, and has received little attention in terms of research and policy decisions in the Indian Ocean. The loss and damage attributable to ocean acidification may not be easily evaluated due to the other pressing concerns; however, the eventual impacts may be exacerbated for this same reason. Some of the marine resource issues of the region include: coastal eutrophication, seawater anoxia, sedimentation of reefs, coral bleaching, mangrove deforestation, overharvesting, destructive fishing, decreasing productivity and shifting distributions of fish stocks.

Fishing is a primary subsistence activity for people throughout the Indian Ocean. Under-nutrition represents a widespread problem. For example, artisanal fisheries of the WIO are the mainstay of coastal livelihoods, providing a vital source of protein and income. Nevertheless, twelve of the twenty countries with highest burden of under-nutrition (representing 80% of the world's undernourished children) are found in East Africa, South Asia, and Indonesia. For the WIO, artisanal fisheries harvest a diverse range of species including: molluscs, lobster, octopus, sharks, mackerel, tuna, and demersal fish from coral reefs and other habitats. The relative contribution of these fisheries is highly variable between countries. Effects of ocean acidification to fisheries will have far-reaching impacts.

Socioeconomic impacts of ocean acidification arise through direct effects on species, and through indirect effects on food or habitat resources, which in turn alter the availability or quality of species or natural resources of interest. Negative direct impacts on small-scale fisheries and mollusc mariculture can be anticipated based on scenarios of decreasing pH by 0.5

units, projected based upon CO_2 emissions to the end of this century. The S Australian scallop fishery and farming of oysters, abalone, scallops and pearl oysters would experience negative effects on calcification and larval survival under such conditions. Positive impacts may be anticipated on seaweed farming and fishing for seagrass-dependent species. Fleshy seaweeds and seagrass productivity is enhanced in elevated CO_2 and benefit would pass to household livelihoods involved in the culture or harvesting of marine plants. Potential indirect impacts may be expected for ornamental fisheries of corals and reef fish for the aquaria industry due to loss of quality and area of tropical reefs. A main macro-economic concern exists for impacts to tuna fisheries due to reduction or loss of fish productivity of smaller pelagic fish (prey) species. Unknown, but potentially significant, impacts may also occur due to losses of reef-based tourism and coastal protection through diminished structure, quality and integrity of coral reefs under conditions of advanced acidification.

Small-scale fisheries represent over 90% of the marine catch of fish in many of the countries of the WIO. Each country's fishery employs tens to hundreds of thousands of people, and is a vital source of food security and income for coastal communities. Mariculture varies greatly among the countries in species harvested and economic importance. Impacts of ocean acidification on mariculture will vary based on the effects and resilience of the species. Numbers for marine-related tourism due to reefs or other coastal natural resources were not reported, but represent another significant part of the lives of the coastal communities of the Indian Ocean.

Several recommendations were posed for the Indian Ocean in response to ocean acidification impacts on fisheries and aquaculture: (1) urgently implement best practices in fishery and ecosystem based management, (2) shift toward aquaculture of more resilient species and breeds of fish, (3) invest in monitoring and long-term research using sentinel marine sites, (4) build adaptive capacity of marginalised and vulnerable coastal communities, and share best practices, information and adaptation options, and (5) recognise the blue carbon value of coastal ecosystems such as seagrass and mangroves and protect habitats by banning destructive practices and fishing gears.

1. THE SPECIFICITIES OF THE REGION

1.1. Geography

The Indian Ocean (Figure 1) comprises 20% of the World's surface water, has an austral to tropical temperature gradient, is bounded to the east by the African continent, to the north by the Asian land mass (which includes semi-enclosed seas - the Red Sea, Arabian Gulf, Gulf of Thailand and Bay of Bengal), and to the West by SE Asia (Thailand, Malaysia, Indonesia, Timor L'Este and Australia). The throughflow between the Indian and Pacific Oceans is known as the Australasian Mediterranean Sea (Tomczak and Godfrey, 2003).

Atmospheric conditions driving the weather and climate across the Indian Ocean are strongly tied to processes that originate across the Indian Ocean (both north and south of the equator), and in the Pacific Ocean that are transmitted into the Indian Ocean through the Indonesian Throughflow (ITF) and El Niño/ La Niña. The primary, relevant climatic phenomena affecting the tropical zone of the Indian Ocean are the El-Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), both of which have direct impacts on rainfall patterns and sea surface temperature.

During the austral winter (May-October) the southeast (SE) Monsoon is dominant as a result of the (boreal summer) heating of the large landmasses of the Indian Subcontinent and Asia. During the austral summer (November-April), the SE trade winds are weaker and the monsoon reverses due to significant (boreal winter) cooling of the Indian Subcontinent and Asia giving rise to the weaker northeast trade winds.

The principle ocean currents of the WIO are presented in Figure 1. The major current, running throughout the year, is the westward-flowing South Equatorial Current (SEC) located in a band around approximately 15-20°S. The SEC is driven by a number of processes including forcing by the ITF and, through the SE Trades, by atmospheric processes associated with the heating of the Indian/South Asian landmass, as well as by equatorial oceanic heating and the formation of the Hadley Cells (Han *et al.,* 2014; Schott *et al.,* 2009).

Deep water circulation is controlled primarily by inflows from the Atlantic Ocean, the Red Sea, and Antarctic currents. The minimum surface temperature exceeds 28°C (82 °F) in the northeastern Indian Ocean. North of 20° South latitude the minimum surface temperature is 22°C (72°F). Southward of 40° South latitude, sea surface temperatures drop quickly to below 4°C (40°F).

Surface water salinity ranges from 32 to 37 parts per thousand, the highest occurring in the Arabian Sea and in a belt between southern Africa and south-western Australia. Pack ice and icebergs are found throughout the year south of 65° South latitude. The average northern limit of icebergs is 45° South latitude.

The main area of sea shelf is the Northwest Australasian Shelf, through SE Asia and the Bay and Bengal. Fringing reefs, mangrove and seagrass habitats are the dominant form of shallow-water environment in the tropical and sub-tropical zones.

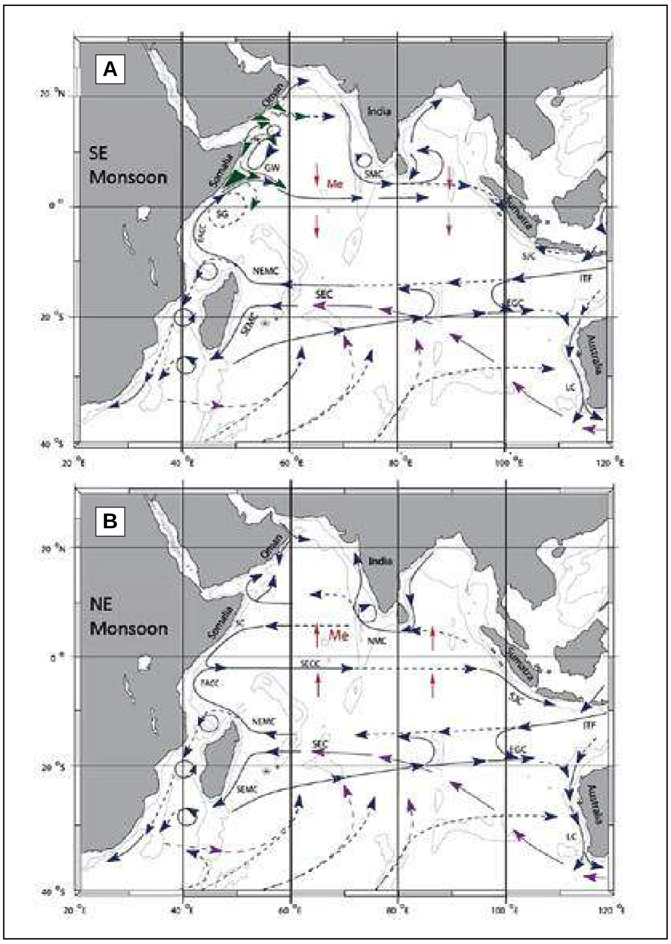

Figure 1:

The Indian Ocean and its currents during the a) South East Monsoon and b) NE Monsoon
(Schott *et al.,* 2009).

The main riverine inputs are from the South Asian landmass - the Shatt-Al Arab and Indus draining into the Persian Gulf and Arabian Sea, respectively, and the Ganges/Brahmaputra and Irrawaddy rivers into the Bay of Bengal. From tropical and sub-tropical Eastern and Southern Africa flow the Tana, Rufiji, Zambezi and Limpopo rivers.

Much of this review is focused on the Western Indian Ocean (WIO) region which lies within FAO statistical area 51 and comprises ten countries: Somalia, Kenya, Tanzania, Mozambique, South Africa, Madagascar, Comoros, Seychelles, Mauritius and the dependent Rodrigues, and the French dependent territory of La Réunion (France). The region has a mainland coast that extends over 11,000 km (with over 3000km in Somalia) and a coastal population of over 20 million which is projected to double as a result of migration and birth, reaching 40 million by 2020 (Olsen *et. al.,* 1999).

The marine ecosystems of the WIO are typified by coral reefs through the tropical zone merging with sandstone marginal reefs in South Africa; extensive mangrove forests and seagrass beds on the African mainland and in Madagascar; sandy beaches, muddy bays, rocky shores, fossil coral reef coastlines and islands (e.g. Zanzibar); granitic and volcanic oceanic islands (Seychelles, Comoros) and atolls. This diverse array of coastal resources in the WIO region provides for key livelihood activities including fisheries and tourism. Others are aquaculture, shipping, mineral exploitation including most recently oil and gas, agriculture and forestry. There are marked differences between countries in terms of development and fisheries: the highest dependence on fisheries is found in Quirimbas, northern Mozambique and Andavadoaka, Madagascar, with over 80% of households in each of these areas dependent on marine resources for food and income (Loper *et al.,* 2008).

1.2. Main Stressors

Quality of life of coastal communities in the WIO region is inextricably linked to the quality of coastal resources. Over the past decade, trends in socio-economic indicators have declined (Loper *et al.,* 2008). The main regional drivers of change include: destructive and unsustainable pelagic and coastal fishery practices (dynamite and overfishing), climate change, land-based sedimentation, watershed pollution and soil runoff, population growth, poorly planned infrastructure, tourism and shipping activities. Increase in human pressure on coastal and marine resources in the WIO region is evident from decreasing fish catches, increasing use of destructive fishing practices and by the increasing volume of untreated sewage and nutrient runoff released into near-shore areas. The main stressors for this area have local, regional and global sources:

- Eutrophication & land-source pollution from nutrients and sewage;
- Sediment impacts on reefs;
- Hypoxia and ‘dead zones’ (e.g. in Bay of Bengal);
- Overharvesting, overcapacity of marine resources, illegal and destructive fishing;
- Mangrove deforestation;
- Impacts of rising sea surface temperature, UV light, & doldrums on coral reefs (Maina *et al.,* 2008, 2011);
- Climate change impacts (sea level rise, rainfall and primary productivity changes, coral bleaching) shifting distribution & productivity of fish stocks;
- Decreasing aragonite saturation and ocean pH, surface water warming, increased stratification of the water column resulting in nutrient limitation and decreasing productivity and deoxygenation are projected to continue in this ocean area this century (Figure 2, Gruber, 2011).

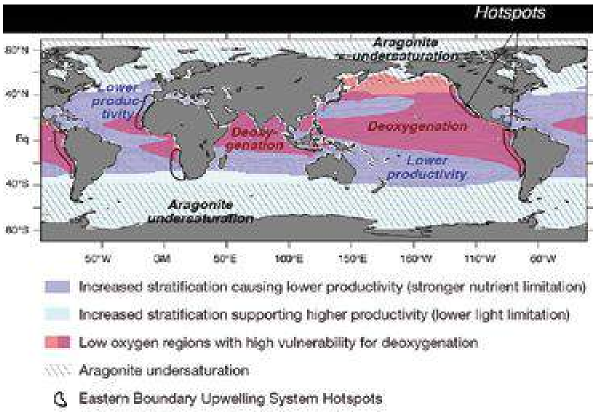

Figure 2:

Source: Gruber, 2011. Modified.

1.3. General socio-economic aspects of the area

Twelve of the 20 countries with the highest rates and prevalence of child malnutrition border the Indian Ocean (Figure 3, Black *et al.,* 2008).

Fisheries of the WIO countries can be categorised into two different types: i) coastal artisanal fisheries fished by local fishers (in territorial waters) and ii) offshore commercial or industrial scale fisheries (in EEZ waters) fished largely by foreign fishing fleets, though this varies considerably between countries (Everett *et al.,* 2010). This overview focuses on national artisanal fisheries as these play a more direct role in the socio-economics of each country.

Artisanal fisheries of the WIO are the mainstay of over 20 million coastal peoples’ livelihoods, providing a vital source of protein and income (Olsen *et al.,* 1999). To our knowledge there has been no specific research on the impacts of ocean acidification on these fisheries, and hence on the people who depend on fishing for their livelihoods. The socio-economic impacts of ocean acidification on coastal communities in the WIO have not been studied and the biological and ecological impacts of ocean acidification on fisheries in the WIO are also unknown.

The WIO artisanal fisheries harvest a diverse range of species including: molluscs, lobster, octopus, sharks, pelagic fin-fish such as mackerels and tunas, both near and offshore, and demersal fish including coral reef fish and those from other habitats. The relative contribution of these fisheries varies considerably between countries.

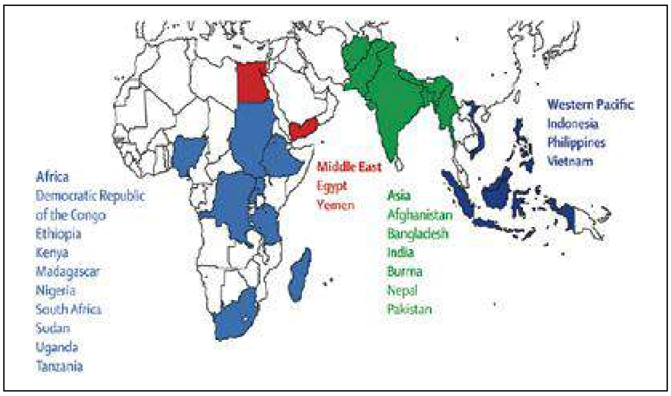

Figure 3:

The 20 countries with the highest burden of under-nutrition: countries with stunting prevalence ≥20% in children under the age of 5 years that together account for >80% of the world's undernourished children. Colour denotes region
(Black *et al.,* 2008).

Fish species targeted by fisheries of the WIO

The fish species targeted by fisheries of the WIO include the following:

Hakes, Cape rock lobster, Yellowfin tuna, Cape horse mackerel, Bigeye tuna, Skipjack tuna, Porgies, Panga sea bream, South American pilchard, Natantian decapods, *Penaeus* shrimps, Indian oil sardine, Drums or Croakers, Bombay duck, Indian mackerel, Herrings, Perch-likes, Cutlass fishes, Anchovies, Jacks and Pompanos, Emperors, Narrow-barred Spanish mackerel, Groupers, Lizard fishes, Snappers, *Sardinella*, Indian mackerel, Rabbit fishes, Seer fishes, Wrasses, and Halfbeaks.

2. BIOLOGICAL IMPACTS OF OCEAN ACIDIFICATION

From studies elsewhere (e.g., Lam *et al.,* 2014), we know the ocean acidification impacts on these different taxa are likely to vary substantially. This WIO context therefore provides an ideal experimental situation for modelling and quantifying the socio-economic impacts of ocean acidification on coastal artisanal fisheries. The implications of the results will be critical for determining mitigation and adaptation measures.

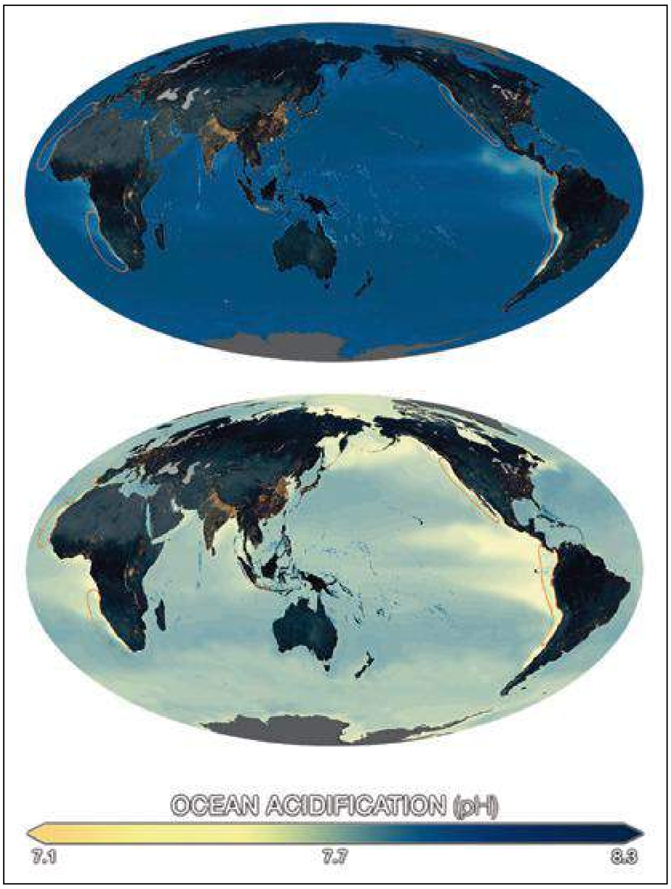

Figure 4:

Projections of decrease in ocean pH from start of the industrial revolution (upper figure) to 2100 (lower figure)
(from IGBP, IOC, and SCOR (2013)
Ocean Acidification Summary for Policy Makers).

2.1. Individual level and Population/community level

No experimental studies on acidification impacts have been conducted in the region to date, the only available data are from similar species in other regions. Projections of aragonite saturation from global models are available for the Indian Ocean (Figure 4), but projections from regional and coastal models are not yet available. The global projections show that ocean acidity (pH) has already declined across the global ocean by 30% (0.1 pH unit) and by the end of this century will decline by 100-150% (0.3-0.4 pH unit) if CO_2 emissions continue at the same rate.

The following lists current status of observational data:

- pH monitoring studies are beginning in India, elsewhere there is little monitoring so there is no long term observational pH data available;
- Fisheries and aquaculture production data are available from 'Sea around us' project and catch-reconstructions;
- Contribution of marine resources to human nutrition, employment and revenues are available from FAOSTAT.

2.2. Consequences at the socio-economic scale

No observational or direct experimental data or studies on acidification impacts have been conducted in the region so we use data on similar species from other regions (average effect-sizes of impact, from meta-analysis).

Potential direct impacts of acidification on Indian Ocean fisheries and aquaculture:

— *Negative effects on small-scale fisheries:*

- SE Asia, S Asia, E&S Africa, Madagascar; S Australia scallop fishery;
- Small effect relative to over-exploitation and habitat change;

Table 1.

Summary of main effects of likely future ocean acidification on different groups of marine organisms, mostly based on experimental studies from around the world. Note that none of the data is from this region.

Table from Williamson P. & C. Turley, 2012.

Group	Main acidification impacts
Warm water corals	A relatively well-studied group. The great majority of experiments show that increasing seawater CO_2 decreases adult coral calcification and growth, and suppresses larval metabolism and metamorphosis (Kleypas *et al.,* 2006; Cohen *et al.,* 2009; Nakamura *et al.,* 2011. Although most warm water coral reefs will remain in saturated waters by 2100, saturation levels are predicted to decline rapidly and substantially; thus coral calcification is unlikely to keep up with natural bioerosion (Cao & Caldeira 2008; Hoegh-Guldberg *et al.,* 2008, Feely *et al.,* 2004; Silverman *et al.,* 2009). Interactions with other climatic and anthropogenic pressures give cause for concern (Fischlin *et al.,* 2007; Veron *et al.,* 2009).
Cold water corals	The long-lived nature of cold-water corals, and their proximity to aragonite saturation horizons, makes them vulnerable to future shoaling of the ASH. Around 70% of known cold water coral locations are estimated to be in undersaturated waters by the end of this century (Guinotte *et al.,* 2006; Turley *et al.,* 2007). Experiments found the effect of pH change on calcification was stronger for fast growing, young polyps (Maier *et al.,* 2009).
Molluscs	Significant effects on growth, immune response and larval survival of some bivalves (Berge *et al.,* 2006; Bibby *et al.,* 2008, Talmage & Gobler, 2009), although with high inter-specific variability (Gazeau *et al.,* 2007, Miller *et al.,* 2009: Parker *et al.,* 2010). Pteropods seem particularly sensitive (Orr *et al.,* 2005; Comeau *et al.,* 2009 & 2010) and are a key component of high latitude food webs. Molluscs are important in aquaculture, and provide a small yet significant protein contribution to human diet (UNEP 2010).
Echinoderms	Juvenile life stages, egg fertilization and early development can be highly vulnerable, resulting in much reduced survival (Kurihara & Shirayama, 2004; Dupont *et al.,* 2008, Clark *et al.,* 2009). Adult echinoderms may increase growth and calcification; such responses are, however, highly species specific (Dupont *et al.,* 2010).
Crustaceans	The relative insensitivity of crustaceans to ocean acidification (e.g. Kurihara & Ishimatsu, 2008, Arnold *et al.,* 2008, Ries *et al.,* 2009) has been ascribed to well-developed ion transport regulation and high biogenic content of their exoskeletons (Kroeker *et al.,* 2010). Nevertheless, spider crabs show a narrowing of their range of thermal tolerance by ~2˚C under high CO_2 conditions (Walther *et al.,* 2009).
Foraminifera	Shell weight sensitive to CO_3^{2-} decrease in the laboratory (Bijma et al, 2002) with field evidence for recent shell-thinning (Moy *et al.,* 2009; de Moel *et al.,* 2009).
Fish	Adult marine fish are generally tolerant of high CO_2 conditions (Ishimatsu *et al.,* 2008; Melzner *et al.,* 2009a,b). Responses by juveniles and larvae include diminished olfactory ability, affecting predator detection and homing ability in coral reef fish (Munday *et al.,* 2009, 2010) and enhanced otolith growth in sea bass (Checkley *et al.,* 2009).
Coralline algae	Meta-analysis (Kroeker *et al.,* 2010) showed significant reductions in photosynthesis and growth due to ocean acidification treatments. Elevated temperatures (+3°C) may greatly increase negative impacts (Martin & Gattuso, 2009). Field data at natural CO_2 vents show sensitivity of epibiont coralline algae (Hall-Spencer *et al.,* 2008; Martin *et al.,* 2011).
Non-calcified macro-algae; sea grasses	Both groups show capability for increased growth (Hendricks *et al.,* 2010; Kroeker *et al.,* 2010). At a natural CO_2 enrichment site (Hall-Spencer *et al.,* 2008), sea grass production was highest at mean pH of 7.6.
Coccolitho-phores	Nearly all studies have shown reduced calcification in higher CO_2 seawater, as first found by Riebesell *et al.,* (2000). However, the opposite effect has also been reported (Iglesias-Rodriguez *et al.,* 2008),and ocean acidification impacts on coccolithophore photosynthesis and growth are equivocal, even within the same species. This variability may be due to the use of different strains (Langer *et al.,* 2009) and/or experimental conditions (Ridgwell *et al.,* 2009).
Bacteria	Most cyanobacteria (including *Trichodesmium*, a nitrogen-fixer) show enhanced photosynthesis and growth under increased CO_2 and decreased pH conditions (Hutchins *et al.,* 2007, 2009). Heterotrophic bacteria show a range of responses with potential biogeochemical significance, including decreased nitrification and increased production of transparent exopolymer particles (affecting aggregation of other biogenic material and its sinking rate) (Liu *et al.,* 2010). Adaptation by bacteria to a high CO_2 world may be more rapid than by other groups (Joint *et al.,* 2010).

- Local acidification could be regulated by better coastal/habitat management.

— *Negative effects on mollusc mariculture:*

- Abalone farms (Australia, South Africa);
- Oyster farming (throughout the region);
- Asian moon scallop (*Admusium*) – SE Asia;
- Pearl oyster farming (Zanzibar, Indonesia).

— *Positive impacts on seaweed farming and fishing for sea-grass dependent species:*

- Enhanced growth of fleshy seaweeds, flourishing algal and sea grass habitats (but may be at the expense of other species);
- Benefits of seaweed culture productivity increases to household livelihoods and SME development.

Potential indirect impacts of acidification on Indian Ocean fisheries and aquaculture:

— *Capture fisheries:*

- Ornamental fisheries for corals and reef fish (small niche industry for aquaria);
- Fish production, diversity, value of reef fish may be affected by reductions in reef area or habitat structure;
- Unknown but potentially significant impacts on cephalopod, echinoderm and finfish fisheries;
- Concerns for food security are small-pelagic and near-shore sea-shelf and reef-associated fisheries (throughout the region);
- Macro-economic concerns are for large pelagic fisheries, particularly tuna fisheries (Maldives, Seychelles, Sri Lanka, Indonesia).

— *Unknown but potentially significant Impacts beyond fisheries and aquaculture:*

- Reductions in reef quality and extent affects reef based tourism and associated livelihoods and economic benefits (e.g. Maldives, Seychelles, East African Coast, Andaman Coast of Thailand);
- Reduction in reef formation may reduce coastal protection from storms and increase erosion and storm damage;
- Positive benefits to seagrass dominated coasts.

3. ECONOMIC IMPACTS OF OCEAN ACIDIFICATION

3.1. Current data

Fish landings and landed values from fisheries of the WIO[1]

The following graphs summarises landings and landed values of fish caught in the WIO, split according to the various large marine ecosystems [the Red Sea, Somali Coast, Agulhas Current, Arabia Sea and the High Seas] within the WIO.

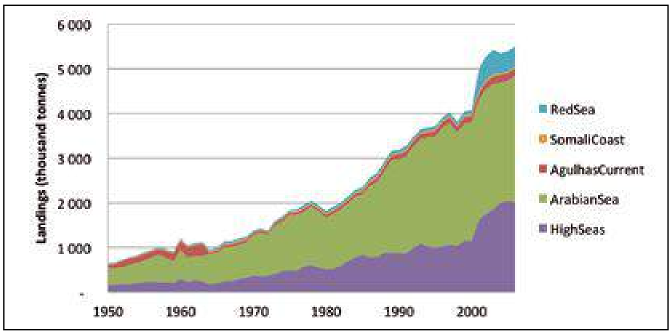

Figure 5:

Marine fish landings from the Western Indian Ocean by marine ecosystem.

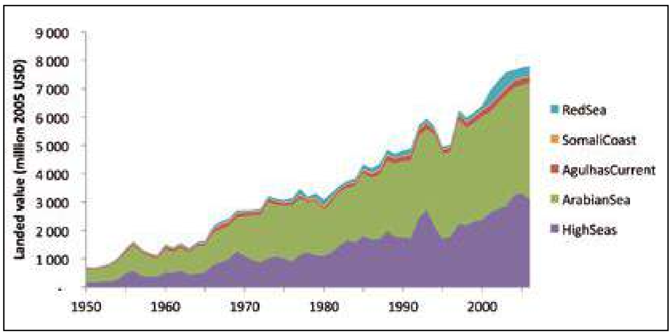

Figure 6:

Marine fish landed values from the Western Indian Ocean by marine ecosystem.

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[1] The data used to draw these graphs are taken from the *Sea Around Us* project website (www.seaaroundus.org) whose basis are reported in Watson *et al.*, 2004 and Sumaila *et al.*, 2007.

Because tuna is a very important commercial group of fish species caught in the WIO, tuna landings and landed values are presented in Figures 7 & 8.

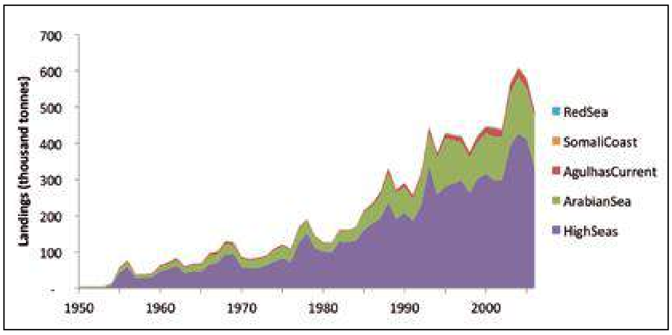

Figure 7:

Tuna landings from the Western Indian Ocean by marine ecosystem.

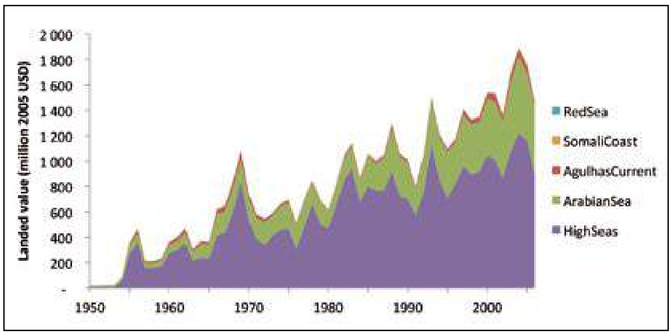

Figure 8:

Tuna landed values from the Western Indian Ocean by marine ecosystem.

3.2. Role of fisheries in the economy

To demonstrate how important the fisheries of the WIO are to the people (especially small-scale fishers) of the region, the following describes the contribution of small-scale fisheries and mariculture operations in the following countries of the region: Comoros, Kenya, Madagascar, Mauritius, Mozambique, Seychelles, South Africa, Somalia, and Tanzania[2].

Mauritius

Small-Scale Fisheries

The Fisheries in Mauritius employ an estimated 11,000 people and contributes 1.5% to GDP. Artisanal fishers have an income level of around Rs300[3] per day, while monthly consumption expenditures for all fishers are, on average, above Rs 4,000. Total domestic catch in the sector is valued at Rs 1 billion. However, catch by the artisanal sector dropped by nearly 360 tonnes between 2004 and 2008, which correlates to the declines in total catch during the same period.

The fisheries sector employs an estimated 2,000 people, 78% of whom are between the ages of twenty to forty five. The number of fishers increased between 2005 and 2008, while production in the sector, unlike Mauritius, increased during the same period. The artisanal sub-sector supplies the majority of fish caught domestically, however, 60% of all domestic fish consumption is imported.

Mariculture

Only one mariculture farm is active in Mauritius and Rodriguez, with cage culture being utilized to produce gold-lined sea bream, red drum and cobia in Mahebourg. The farm produces both for domestic consumption and export, employing 65 people and, in 2008, produced an estimated 750 tonnes of fish. The sector is not yet a major part of the country’s economy, however, six mariculture licenses have been granted as of 2009 and the government has identified the sector as having great potential for growth, thus, activity is likely to increase in the near future.

Madagascar

Small-Scale Fisheries

The small-scale fishery in Madagascar made up of subsistence, artisanal/traditional and recreational fishing, is largely concentrated on the country’s west coast. This sector employs 36% and 27% of the workforce in the provinces of Toliara and Mahajanga, respectively. Traditional fishing, undertaken mostly by canoe, represents nearly 68% of total fish catch, largely focusing on export products, such as crustaceans, holothurians and cephalopods. Men make up 97% of the workforce. In 2003, the small-scale fisheries, as a whole, contributed nearly

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[2] This section draws on the work reported in the “Overview of Coastal Livelihoods in the Western Indian Ocean” Report prepared by Dr. Tim Andrew and his collaborators.

[3] 100 Mauritian rupees = 3.66 U.S. dollars as at May 8, 2011.

26% of the total tonnage of fisheries export and nearly 9% of the total value of exports, worth an estimated $142 million USD.

Mariculture

Mariculture is a developing sector in the Madagascan economy. There is currently on-going research and pilot projects studying the feasibility of farming mud crab, sea cucumber, blue-green algae, oyster and eel. There are also commercial activities present, seen with the large scale farming of prawn for export and domestic consumption, as well as small-scale production in seaweed. Prawn farming, in particular, has been very successful in providing employment for rural communities, supplying 4,325 permanent and 30,000 part time jobs in 2003. The sub-sector has a strong export component worth an estimated $62 million USD.

South Africa

Small-Scale Fisheries

It has been estimated that nearly 100,000 people are directly involved in the sector, while upwards of 28,000 households are dependent on subsistence fisheries. The commercial fishery contributes 0.5% to GDP and brings in R80 billion annually. Commercial fisheries include some aspects of the small-scale sector (for example west coast rock lobster and traditional line fish). As a whole, small-scale fishing along the east coast has traditionally focused on shore-based activity as a means of livelihood, while small-scale fishers along the west coast have normally been drawn into the commercial fishery.

Mariculture

Medium and large-scale mariculture activity is well established in South Africa, with commercial farming prevalent in abalone, seaweed, mussels and oysters, and pilot commercial projects underway in dusky Kob, silver Kob and yellowtail finfish. Research is also ongoing for the production of clownfish, white margined sole, west and east coast rock lobster, scallops and bloodworms. Small-scale production is, however, scarce in the country, as most projects are being developed by the private-sector with an emphasis on pump ashore systems. This lack of small-scale production has been attributed to several factors, including poor environmental conditions, inadequate participatory approaches, poor fish growth, very low returns, lack of interest and neglect. Medium and large-scale farms are, nevertheless, providing employment outside urban areas, particularly in the Eastern and Western Cape.

Seychelles

Small-Scale Fisheries

The small-scale fishery in Seychelles, which includes the artisanal and semi-industrial sub-sectors, contributes between 1% and 2% to GDP annually, while the fisheries sector, as a whole, contributed 7.7% in 2008, an increase of 1.3% from 2004. Seychelles has very limited land-based opportunities, thus, the fishery is a vital source of income, employment, food security and foreign exchange in the country. Reliance on the sector is most evident in the fact that 17% of the total population is employed in the fishery, 30% of which are active in the small-scale sector, while 10% of the population is directly dependent on the small-scale sector.

Mariculture

Few mariculture activities are currently operational in Seychelles, with only prawn, giant clam and pearl oysters being produced in small-scale commercial operations.

Prawn and clam production has also been decreasing in recent years, with clam production falling from 1,960 tonnes in 1996 to 585 tonnes in 2006 due to weak demand, while prawn production fell from 1175 tonnes in 2004 to 704 tonnes in 2006.

Farming of clam and pearl oysters are not labour intensive practices, thus, little employment has been generated around the sub-sectors, and while the prawn farm on Coëtivy Island employs 350 people, only 18% are actually native Seychellois.

Comoros

Small-Scale Fisheries

The small-scale fisheries in Comoros employ 6% of the country's population, with women mainly being employed in post-catch operations, while 30% of the population is dependent on the fishery. The sector contributes 8% to GDP, 24% to agriculture GDP and also makes up 5% of total foreign exchange annually, making fishing not only a net supplier of foreign exchange, but also a key component of the country's balance of payments. The small-scale fishery is, in this respect, a vital link to the global economy for the Comoros.

Mariculture

With no designated mariculture zones, limited fresh or brackish water resources, and limited areas suitable for culture, there are currently no operating mariculture activities in the country.

Somalia

Small-Scale Fisheries

There is an operative small-scale fishery in Somalia with approximately 50 fishing centers and an estimated 30,000 people from coastal communities engaged. Despite rich biodiversity and an extensive coastline, exports of fishery products only account for around 3% of total exports and contribute about 2% to GDP, though it is difficult to verify these figures. Household income in the sector also fluctuates by season, with fishers earning US$1.5 per day during monsoon season and an estimated US$40 per day during fishing season.

Mariculture

A dedicated report on mariculture has not been included in this country report due to the current difficulty in obtaining detailed information on the potential of this sector in Somalia.

Kenya

Small-Scale Fisheries

The small-scale fisheries in Kenya, defined as artisanal in the country report, employs 10,000 people and supplies 95% of the country's total marine catch, generating an estimated US$ 3.2 million per year and accounting for between 2% and 6% of total fish production in the country. An estimated 60,000 coastal residents depend on the sector, wherein, the level of dependence is higher in regions with low development, less salaried employment and high poverty rates. Hence, while the entire fisheries sector only contributes 0.5% to national GDP, it is nevertheless a vital component to economic activity in the coastal regions.

Population growth, along with high levels of poverty in the coastal regions, has contributed to increases in the number small-scale fishers, with a 34% increase documented between 2004 and 2008. This has, in turn, placed great strain on fish stocks along the coast, resulting in the over-exploitation of fisheries resources. This has subsequently resulted in an overall decline in small-scale landings, evident in the 50% decrease in demersal coral reef fish yields through the 1990s. Rabbit fish and emperor fish, which make up nearly 40% of the small-scale fishers' landings, declined by 40% in the 1990's. The catch of tuna has been declining since 2004. Destructive fishing techniques, such as the use of seine nets have facilitated these declines; however, population growth and poverty in the coastal regions have been documented as the key contributing factors.

Mariculture

There are several mariculture activities currently in the experimental stage along the south coast of Kenya. This includes eight finfish farms, six crab farms and four prawn farms, all of which are currently producing for domestic consumption. This development is a reflection of not only the high-quality seawater in the coastal region, but also the enthusiasm of coastal communities to develop mariculture activities. Many mariculture operations, particularly crab and finfish, are also being developed as community-based initiatives, again a testament to the willingness of coastal residents to become involved in the sector. Thus, despite inadequate coordination and planning in the sector, mariculture is a developing field in the Kenyan economy.

Tanzania

Small-Scale Fisheries

The small-scale fisheries in Tanzania accounts for 98% of total fish production, 1.3% of GDP and makes up 9.9% of fish exports worth an estimated $12.4 million USD. While its contribution to GDP may appear marginal, the sector is a vital source of food security, employment and income for coastal communities, which subsequently stabilizes the five coastal regions which, when including all sectors, make up 32% of Tanzania's GDP.

Mariculture

Mariculture is clearly a vibrant sector in the Tanzanian economy, with finfish, seaweed and mud crab being farmed in all coastal regions, and pearls and prawns also being farmed in Mafia and Tanga. Regulation and infrastructure development has lagged behind in this sector, however, high quality seawater, large numbers of candidate species and existing research and support capacity highlight the untapped potential in the sector.

Mozambique

Small-Scale Fisheries

Comprised of subsistence, semi-industrial and artisanal fishing, the small-scale fishery in Mozambique employs over 351,700 people, 2% of which are women. It accounts for 93% of the country's total marine catch, 91% of which is caught by the subsistence and artisanal fishers and 2% by the semi-industrial sub-sector. Income levels in the small-scale fisheries are largely dependent on position within the sector, whereby, three broad positions are classified in the report; Boat and gear owners, crew (employees) and fishing by foot/collectors. Income in the sector is dependent on region, and subsequently distances to market.

Mariculture

Mariculture employs 2,000 people in commercial seaweed farming, 80% of which are women, and 1,000 people in commercial prawn farming, and is thus a strong developing sector in the Mozambican economy. There are also experimental projects underway in finfish and mud crab, which highlight the opportunities for further development in the sector. The country's high quality seawater, its ideal environment for prawn farming, along with its large areas identified as suitable for mariculture development, should only accentuate these growing opportunities.

3.3. Forecast (or scenarios)

Economic studies of the effects of ocean acidification on fisheries in general are very scarce, and such studies for the WIO are virtually non-existent. We can, however, learn from more general studies on this issue in the literature.

It is very likely that the impacts of ocean acidification on fisheries, in general, will take place along with other environmental stresses (e.g. warming, deoxygenation, eutrophication) and non-environmental stress (e.g. overfishing). An increase in ocean acidity would add more stress to the marine ecosystem and the human communities that depend on them.

Increasing dissolved CO_2 in the ocean is very likely to lead to reduced growth of calcifying marine species such as molluscs, which would, in turn, affect the economics of the fisheries that depend on them. Cooley & Doney (2009) estimated substantial revenue declines, job losses, and indirect economic costs in the United States by assuming that the reductions in calcification rate or growth equate to the corresponding decline in molluscs fisheries productivity and revenues. A subsequent study was conducted to identify countries with the most vulnerable to ocean acidification-driven decrease in landings of molluscs (Cooley *et al.,* 2011). Narita *et al.* (2012) also estimated the global and regional economic costs due to loss in the production of molluscs under ocean acidification using partial-equilibrium modelling, estimating a loss of about 6 billion USD.

It is also very likely that ocean acidification will impact coral reefs and the marine species associated with them. An increase in ocean acidity may reduce coral calcification, favour highly invasive non-native algal species, and reduce the biodiversity associated with the reefs. Brander (2007) estimated that the economic impact of ocean acidification on coral reefs will escalate over time under the Intergovernmental Panel on Climate Change (IPCC) CO_2 emission scenarios. The study estimated the economic loss due to the impact of ocean acidification on coral reefs by combining both the impact of CO_2 on coral reef cover and the projected economic value of coral reef using a meta-analysis (Brander, 2007).

Although there is still no detailed study on the economic impact of ocean acidification on global fisheries, it seems reasonable to assume that the direct impacts associated with ocean acidification might eventually impose costs in the order of 10% of marine fishery production, perhaps something in the order of $10 billion/year (Kite-Powell, 2009).

Clearly, work is needed to help reveal the potential impact of ocean acidification on the fisheries of the WIO, in particular, and all the world's large marine ecosystems, in general.

A comprehensive, broad-based approach for understanding the impact of ocean acidification on the marine ecosystem, fisheries, and eventually the socio-economic dimensions, is still scarce (Hilmi *et al.,* 2012). One approach to estimating these impacts is to use "Economic Valuation" based on changes in ex-vessel prices, fishing costs and projected catch under different ocean acidification scenarios. Other than the change in landed value or total revenue, ocean acidification may also affect the cost of fishing by changing the fishing effort needed to catch the same amount of fish, the number of fishing days, travel distance, gear to be employed, etc., when the distribution and abundance of target species are affected by ocean acidification. The wages earned by fishers may also be affected. Since fisheries are a primary or base industry, change in catch potential may also indirectly affect other economic sectors, from boat building to international transport (Dyck and Sumaila, 2010). Thus, it is crucial for us to take these induced and indirect economic activities into account when assessing the full economic impact of ocean acidification on fisheries.

4. CASE STUDIES OR EMPIRICAL EVIDENCE

No experimental studies on acidification impacts have been conducted in the region, the only available data are from similar species in other regions (Table 1). Considering the vulnerability of the populations bordering the Indian Ocean to food security, this is a major finding of this study, and requires urgent attention.

5. POLICY RECOMMENDATIONS

1. Ocean acidification will have direct impacts on select fisheries and aquaculture systems that are of economic importance and will impact food security.

Recommendation: The need to implement best fishery and ecosystem based management practices is even more urgent.

2. Aquaculture likely to be more impacted by ocean acidification than wild harvest because it targets species that are directly impacted by ocean acidification.

Recommendation: Shift away from reliance on wild-caught seed; breed for acidification tolerance.

3. Indirect impacts of ocean acidification on habitats (e.g. coral reefs) and processes (e.g. food webs) are likely to be even more important than direct impacts.

Recommendation: Investment in long-term research and monitoring; choose sentinel sites in countries likely to be impacted.

4. Marginalised and vulnerable groups likely to be negatively affected and be unable to take advantage of opportunities, such as increased seaweed production.

Recommendation: Build adaptive capacity of marginalised and vulnerable coastal communities.

Recommendation: Share best practices, information and adaptation options.

5. Recognise the potential for blue carbon value of coastal ecosystems, e.g. seagrass and mangroves.

Recommendation: This is a knowledge gap that needs to be addressed through research, but in the meantime, protect these habitats, for example through multi-habitat protected areas, banning of destructive gears (such as, beach seines).

6. SUGGESTIONS FOR FURTHER RESEARCH NEEDED TO FILL THE GAP BETWEEN NATURAL SCIENCES AND ECONOMICS

This study has highlighted the scarcity of ocean acidification observational data (of both carbon chemistry and biological impacts) in this region, the lack of studies of vulnerability of socio-economically important species and ecosystems to acidification, the risk these changes may impose on the peoples in this region, and the ability of these societies to adapt to changes. There are currently only two projects completing climate change and fishery risk assessments for species in Western Australia and Northern Australia.

— *Recommendation:* Develop long-term ocean acidification monitoring sites in coastal regions and societies likely to be most vulnerable to ocean acidification to give early warning and forecasting to facilitate societal adaptation.

— *Recommendation:* Address knowledge gaps between both direct ocean acidification impacts on aquaculture and wild harvest target species and the indirect impacts on habitats (e.g. coral reefs) and processes (e.g. food webs) as the latter could likely be more important that direct impacts.

— *Recommendation:* Further research on potential for blue carbon value of coastal ecosystems (e.g. seagrass and mangroves).

Proposed new economic analysis

Base case analysis:

— Determine the impact of ocean acidification increase on species biomass and therefore impact on catch potential;

— Use catch data to compute the potential catch changes for this ocean, in general, and for countries fishing in it;

— Translate the potential economic effects of the projected catch changes (indicators: total revenues, economic impact; income impacts); and

— Assess the impact of catch changes on food security by looking at catches for domestic use and exported fish.

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OVERALL CONCLUSIONS AND RECOMMENDATIONS

The second international workshop on “Bridging the Gap between Ocean Acidification and Economic Valuation” marked the beginning of a process to review the status of knowledge concerning impacts of ocean acidification on fisheries and aquaculture relied upon by countries world-wide for subsistence, revenue, trade, tourism and non-market services. The review from the six regions evaluating socio-economic impacts of ocean acidification has identified both commonalities, as well as, specific circumstances for fisheries based upon physical, biological and economic characteristics. All regions comprise distinct sub-regions and multiple large ecosystems. From these regional characteristics, several important pervasive conclusions and recommendations can be drawn.

A fundamental precept accepted across all regions is that increasing ocean acidification is a global issue with its source being the man-made emissions of carbon dioxide to the atmosphere. The emissions are steadily increasing, and the subsequent absorption into the ocean is causing chemical changes to seawater at a rate unparalleled in the known geologic record for tens of millions of years. The change in conditions of the physical state of ocean waters will have biological effects at the species level, which will translate to ecosystem shifts of unknown proportions and directions. Most evidence points to negative consequences for human activities for communities reliant upon marine resources.

Also common across all regions was the observation that ocean acidification is not occurring in a void. It is one factor among several, such as global warming, low-oxygen ocean areas (hypoxia), high-nutrient waters (coastal eutrophication), and marine pollution (both solid and chemical from land and sea), which will contribute to environmental deterioration. The effect of any combination of these factors is likely to be synergistic and negative. Projections of ocean acidification effects made without consideration of the synergistic result underestimate the true impact and time-scale of the phenomenon.

Despite regional similarities ocean acidification also does not occur or have effect equally across all areas of the world ocean. Certain areas can be considered “hotspots” of acidification due to large-scale ocean processes, namely the Arctic and Southern Oceans, deep waters, coastal upwelling zones, and surface waters subject to multiple stressors. Biologically, organisms with calcium carbonate structures, such as corals and bivalves, are particularly sensitive to changes in carbonate concentration in the water, and thus shallow-water tropical reefs and coastal areas with high bivalve harvest are particularly vulnerable to acidification effects. Numerous species have been studied experimentally and negative impacts predominate for diverse phyla, including echinoderms, corals, molluscs, and calcifying plankton but a large diversity of tolerance across species or even among species occurs. Effects to finfish and molluscs (especially bivalves) have great implication for fisheries and aquaculture in all regions of the world. A common conclusion among all regions is that there remains insufficient available information on fish and seafood species related to sensitivity to ocean acidification.

Importantly, major fisheries and aquaculture activities often occur in ocean areas prone to acidification. This puts economies and dependent livelihoods at risk under scenarios of increased ocean acidification. However, great uncertainty exists concerning effects on finfish for all regions of the world. Research of acidification effects on finfish, especially physiological and early life stages, is in the preliminary stages, and needs further effort and support, in particular for high-value species and those commonly relied upon as food. World capture fisheries and aquaculture generate more than $US 200 billion per year. More than half of the world human population depends upon seafood for 15% or more of their animal protein nutrition. The risk of a global scale acidification event requires consideration by policy makers. Recommendations are made for each of the regions, some of which are represented below.

The **South Pacific and Southern Ocean** include the world’s largest fishery (anchovies), as well as a number of key species in the oceanic food-web, such as pteropods and krill. Negative impacts may weaken trophic stability and have cascade effects other species. Warming in the Southern Ocean may increase primary productivity, and thus may have a positive impact on harvestable fishing, but this is an unknown. General recommendations for the region are to establish coastal water quality monitoring in key fisheries areas, map ocean areas of multiple stressors, and reduce impacts of other threats. For fisheries, ecosystem modelling should be performed to project future risks, timelines and food web scenarios. In aquaculture, breeding for resilient species and insurance risk analysis can be undertaken. The aqua feed industry, major aquaculture companies, and industrial small pelagic producers should engage in planning for ocean acidification impacts. Engagement strategies can include fostering collaboration among Regional Fisheries Management Organizations (RFMO's). Institutional mechanisms can be defined to integrate ocean acidification into the UNFCCC process to maintain a healthy environment.

The **North Atlantic** has the highest proportion of anthropogenic carbon distributed throughout the water column, and the **Arctic** is the region undergoing the fastest rate of acidification, according to global ocean models. Increased water quality monitoring is needed to understand the spatial and temporal variability of the carbonate system to identify local areas most at risk, economically. Areas suitable for future aquaculture can be identified by mapping acidification. Three classes of marine harvest are important in the region; finfish, crustaceans, and molluscs. Of these, molluscs are expected to be negatively impacted to the greatest extent. Warming impacts are expected to include species composition changes and increased productivity, both of which may have positive impacts in the near-term on potential fish catch. Ocean acidification will have a constraint on the anticipated increase, but direct economic impacts will be limited. Biological impacts will be highest for bivalves and echinoderms. Uncertainties exist due to incomplete information concerning acclimation, adaptation, ecological interactions, synergy between stressors, and environmental variability. Due to the uncertainty concerning fisheries and aquaculture impacts, an adaptive management approach in the North Atlantic is recommended. This would support the many local areas with fishing communities, family businesses, and small and medium-sized enterprise (SME's) fish farms, which are highly sensitive to change. Targeted, integrated research on economically-important species, and related ecosystems, using locally relevant scenarios is recommended for these polar and sub-polar northern waters. The regional markets have a high dependence on imports. Therefore, direct effects of ocean acidification in other regions could have significant impacts on local welfare in the North Atlantic. The need for economic assessments with area-specific data was identified. Case studies on specific fisheries and aquaculture operations on a more local level are recommended. Communication remains an important needed vehicle to address public understanding of the issues, technology transfer for monitoring, participatory research, and in policy decision-making.

The **Central and South Atlantic** includes small-scale fisheries throughout the region, and some large-scale fisheries (for example, hake fish). Shellfish harvests and coral habitats are most likely to experience direct effects of ocean acidification. Upwelling regions located in eastern boundary currents have major fisheries, but the effects on finfish are not yet known. Artisanal and small-scale or semi-industrial fisheries and bivalve aquaculture are likely to be impacted for species such as yellow clam, queen conch, and oysters. Coral reef fish species are vulnerable to habitat degradation effects. Vulnerable, economically-important species of the region include: the cupped oyster, ark clams, cuttlefish, short-fin squid, and Patagonian squid and scallops. Economic impacts will likely occur in human coastal communities, as negative effects of ocean acidification will worsen food distribution inequalities that already exist and remove key sources of revenue, reducing regional food security. No information is available on economic impacts to open-ocean finfish fisheries such as hake, tuna, billfish, sardines, and anchovies in this region. Indirect food web effects on open ocean fisheries have not yet been studied. Human adaptation approaches and policy responses need to consider factors such as species sensitivities, human dependence, location of fisheries, and species of interest. Governance should be more robust and adaptive than at present. Fisheries management must build flexibility to allow coastal fishers to change gear and species fished to adapt to changes in abundance and location caused by ocean acidification impacts. Governance support is needed for human adaptation in terms of livelihood diversification and education, especially for the less wealthy and more fishery-dependent subsistence communities. RFMO's should incorporate acidification impacts into planning. Local community-focused adaptation is likely to have greatest effect in responding to changing conditions. More research is needed to understand the sensitivity of certain species to ocean acidification that are high-value commercial harvests such as the crustaceans: lobsters, crabs and shrimp. Coastal monitoring of chemical and physical parameters of ocean water is needed, especially in zones where more vulnerable species are harvested.

The **Mediterranean and Black Seas** are a small but highly-fished area. Ocean acidification effects will manifest both directly and indirectly on capture fisheries and aquaculture. Little information is available on the direct effects of seawater acidification on fish growth and survival due to lack of research on vertebrates. Reduced growth of red corals and decreased immunity of bivalves such as white clams are known from experiments but still unknown in the field. Indirect effects of ocean acidification will include altered primary production, changes in essential fish habitat, including vermetid reefs, sea grass meadows, coralligenous communities, and possibly increased frequency of harmful algal blooms. The result of HABs outbreaks will be impacts on seafood safety and shellfish survival. Ocean acidification effects on jellyfish populations, which are currently experiencing outbreaks in the region, are a major concern. Localized jellyfish overpopulation may have negative impacts on cultivated fish in cages. Bivalves will be negatively impacted by increasing temperature and cumulative ocean acidification effects including reduced calcification of shells, vulnerability of early life stages, reduced reproductive ability, and reduced immune capacity against pathogens. Recommendations for response to ocean acidification in semi-enclosed seas include; (1) enhance multi-stakeholder communication by promoting exchange of knowledge and building reciprocal trust, (2) perform multi-stressor research at various scales, (3) perform integrated blue carbon economic valuation including ocean acidification impacts on other economic sectors such as tourism, (4) address long-term, basin-scale monitoring of pH to assess impacts in productive coastal areas, and (5) identify research gaps for various aquaculture activities.

In the **North and Central Pacific,** ocean acidification will most affect commercial, subsistence and recreation capture fisheries in coral reef habitats through impacts on (a) early life stages of specific organisms (for example, larvae) and (b) habitat structure and function, especially Scleractinian corals. Fisheries of importance and special concern are tuna, shrimp, and sea cucumbers. Ocean acidification will impact aquaculture of molluscs due to the sensitivity of these species, especially oysters and other bivalves, with particular concern for pearl oysters. Potential economic impacts of ocean acidification on gross revenues for United States mollusc fisheries for 2060 are estimated at $US2.5 billion. The impact on world shellfish producer surplus is projected to be $2.3 billion/year by 2100, primarily from China (76%), USA (8%) and Japan (7%). Regional dependence on seafood is very high; protein from coral reef fisheries is more than 50% of total human diets for many countries in the Pacific. The recommendations for the North and Central Pacific region include:

— Incorporate ocean acidification into ecosystem-based and coastal zone management plans to increase the resilience of marine ecosystems.

— Diversify from coral reef subsistence fisheries.

— Assess potential risks to future fish stocks in multi-lateral negotiations of quotas (for example, tropical Pacific tuna).

— Improve monitoring of ocean acidification to minimize impacts.

— Relocate hatcheries to areas with less intensive occurrence of acidification.

— Identify new species for aquaculture production.

— Selectively breed for acidification-resistant strains of species.

— Practice polyculture such as seaweed and pearl oyster farming.

— Evaluate impacts on species which are more important to society (for example, tuna)

— Model food web effects on higher trophic levels.

— Assess the feasibility of adaptation measures, ecological impacts and costs.

Finally, specific case studies are recommended to provide assessments and valuation of impacts on various localized fisheries and aquaculture activities. Some of the ocean acidification case studies suggested include:

— Valuation of the impact on U.S. shellfish hatcheries (such as Whiskey Creek) reduced survival of oyster spat.

— Pearl farming in the Central Pacific—reduced quality of pearl production from reduced aragonite saturation.

— Invertebrate and shellfish farming in East Asia—reduced market value due to development of black spot in Panaeid shrimp.

— Coral reef fisheries—impact of combined effects of warming, acidification, and increased intensity and frequency. Assessing potential negative impacts on reef fisheries due to coral bleaching and degraded habitats.

— Incorporating ocean acidification uncertainties into fishing licensing for tuna.

— Scallop aquaculture in China and Japan.

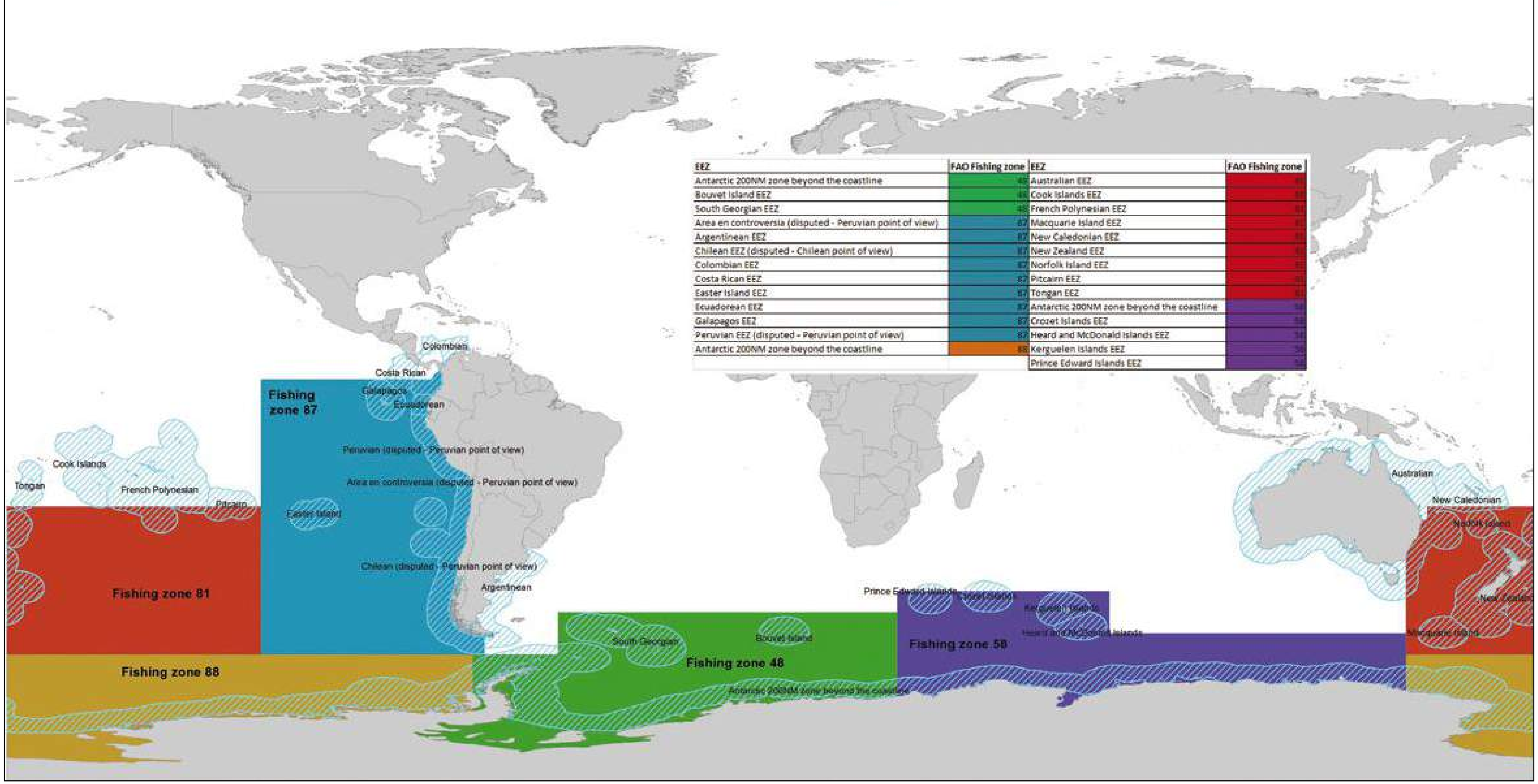
The **Indian Ocean** can expect direct effects on select fisheries and aquaculture systems of economic importance due to ocean acidification. This region has a large human coastal population with direct dependence on capture fisheries and aquaculture for subsistence. The potential risk to food security due to ocean acidification in the region is high. A gap in oceanographic and natural resource information is a barrier to assessing impacts in the Indian Ocean. It is suggested that best fishery and ecosystem-based management practices be implemented urgently. A shift away from wild-caught seed stock is also recommended, and selective breeding toward "acidification tolerance" suggested. Investment in long-term research and monitoring should be supported, and sentinel sites chosen in countries or areas more likely to be impacted. Invest in building adaptive capacity of vulnerable communities. Marginalised and vulnerable groups should be educated and presented with opportunities to adapt. Best practices and information on adaption options should be shared.

The regional approach to assessing impacts of ocean acidification on fisheries and aquaculture used in this report reveals several important points. Primarily, regional differences exist for ocean acidification impacts, based upon ecosystem components present, resource use and adaptative capacity. In all cases, lack of basic information of impacts on fish and economically important species hamper economic evaluation and emphasises the need for research in this area. All regions agree on the essential response of reducing CO_2 emissions, although adaptation measures differ dependent upon region. Diversifying away from reef fisheries and building adaptive capacity in aquaculture methods and species and implementing best practices in fisheries and ecosystem-based management will be key to proactive adaptation. Initiating case studies on local scales will allow for appropriate data collection and evaluation of resources and markets. Such case studies may prove valuable if targeted to species with identified sensitivities, and relevant economic importance.

The Editorial Board

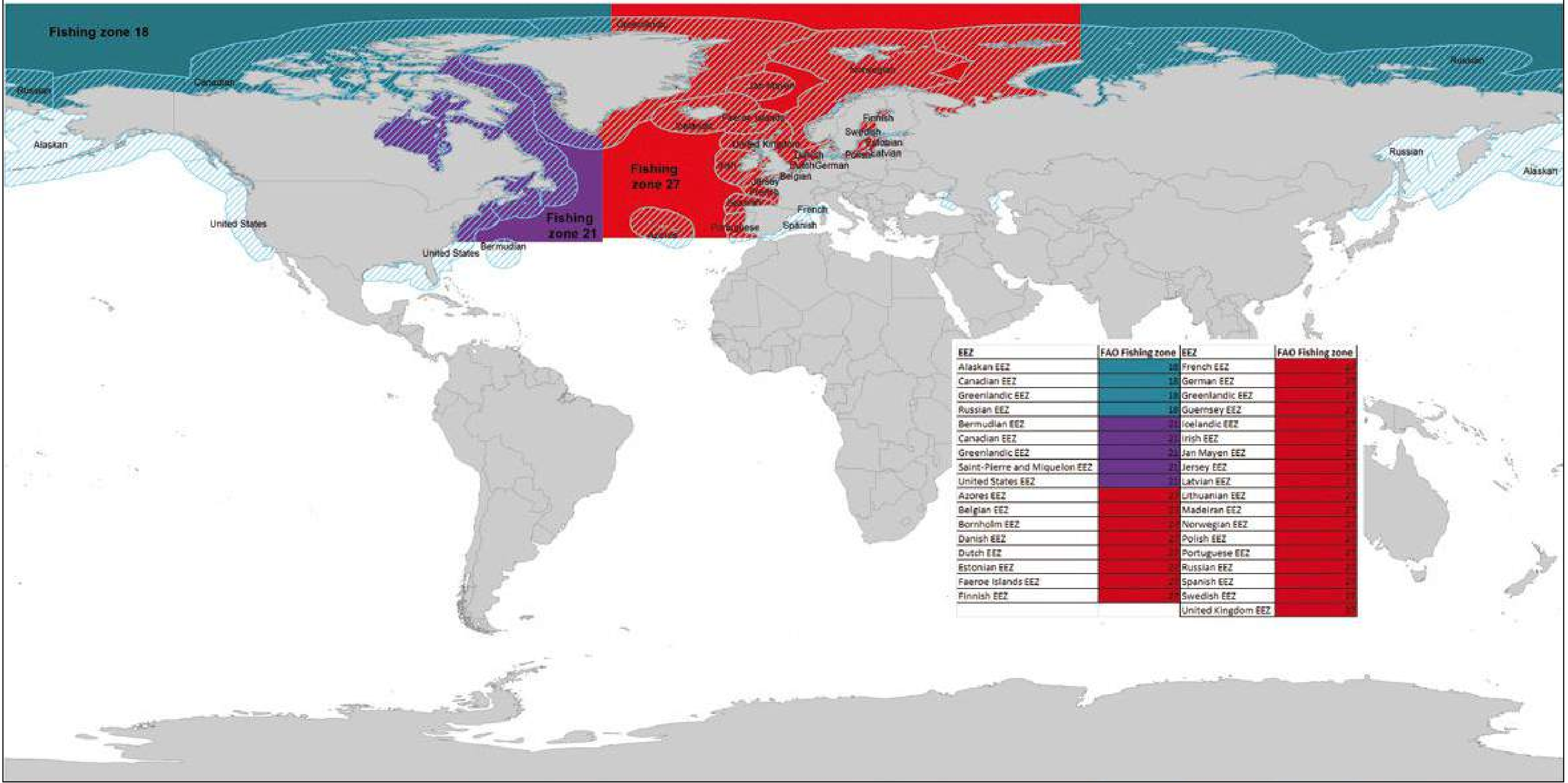
ANNEX 1: MAPS

World exclusive economic zones of FAO fishing region 1

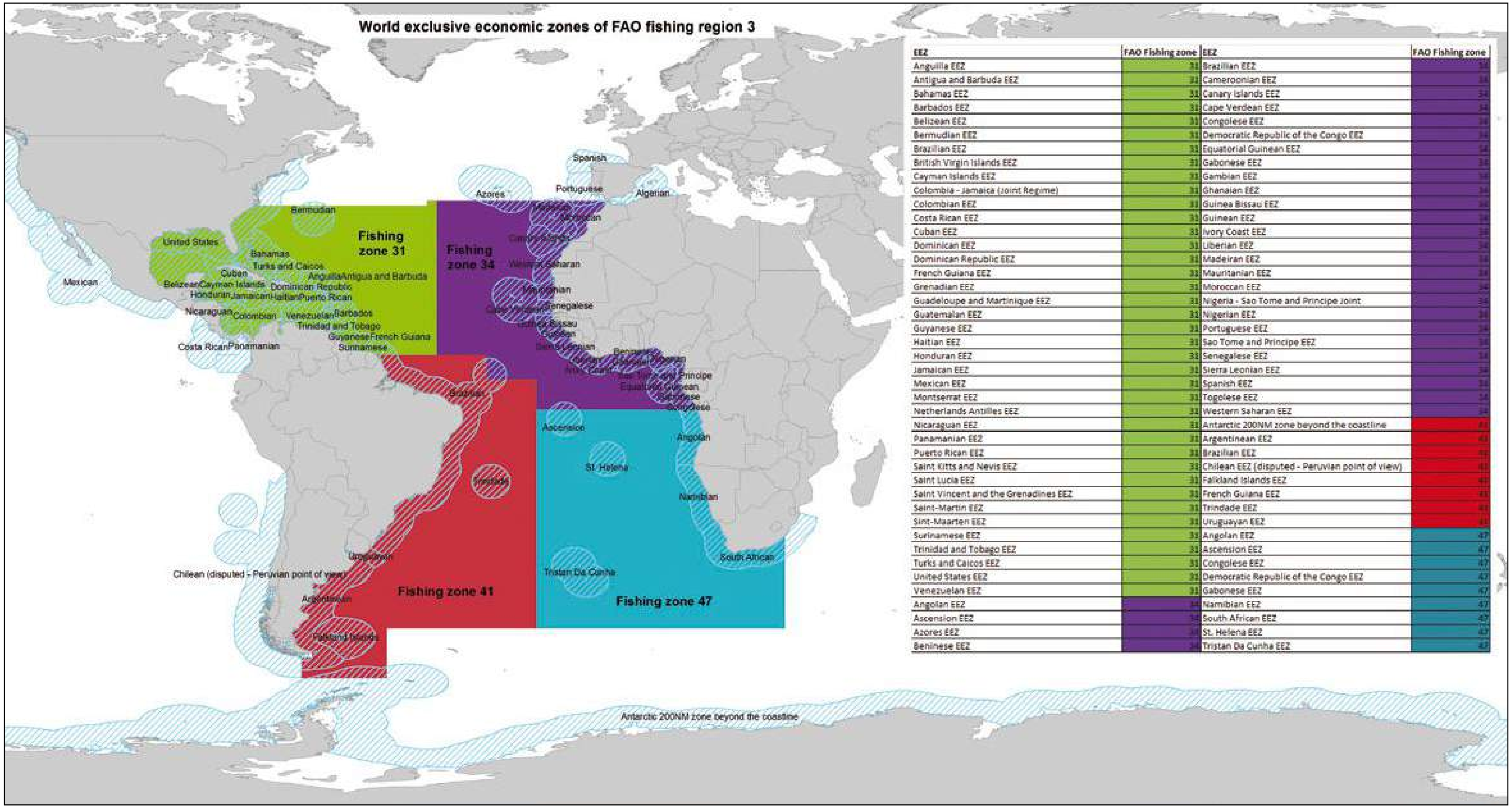


EEZ	FAO Fishing zone	EEZ	FAO Fishing zone
Antarctic 200NM zone beyond the coastline	48	Australian EEZ	81
Bouvet Island EEZ	48	Cook Islands EEZ	81
South Georgian EEZ	48	French Polynesian EEZ	81
Area en controversia (disputed - Peruvian point of view)	87	Macquarie Island EEZ	81
Argentinean EEZ	87	New Caledonian EEZ	81
Chilean EEZ (disputed - Chilean point of view)	87	New Zealand EEZ	81
Colombian EEZ	87	Norfolk Island EEZ	81
Costa Rican EEZ	87	Pitcairn EEZ	81
Easter Island EEZ	87	Tongan EEZ	81
Ecuadorean EEZ	87	Antarctic 200NM zone beyond the coastline	58
Galapagos EEZ	87	Crozet Islands EEZ	58
Peruvian EEZ (disputed - Peruvian point of view)	87	Heard and McDonald Islands EEZ	58
Antarctic 200NM zone beyond the coastline	88	Kerguelen Islands EEZ	58
		Prince Edward Islands EEZ	58

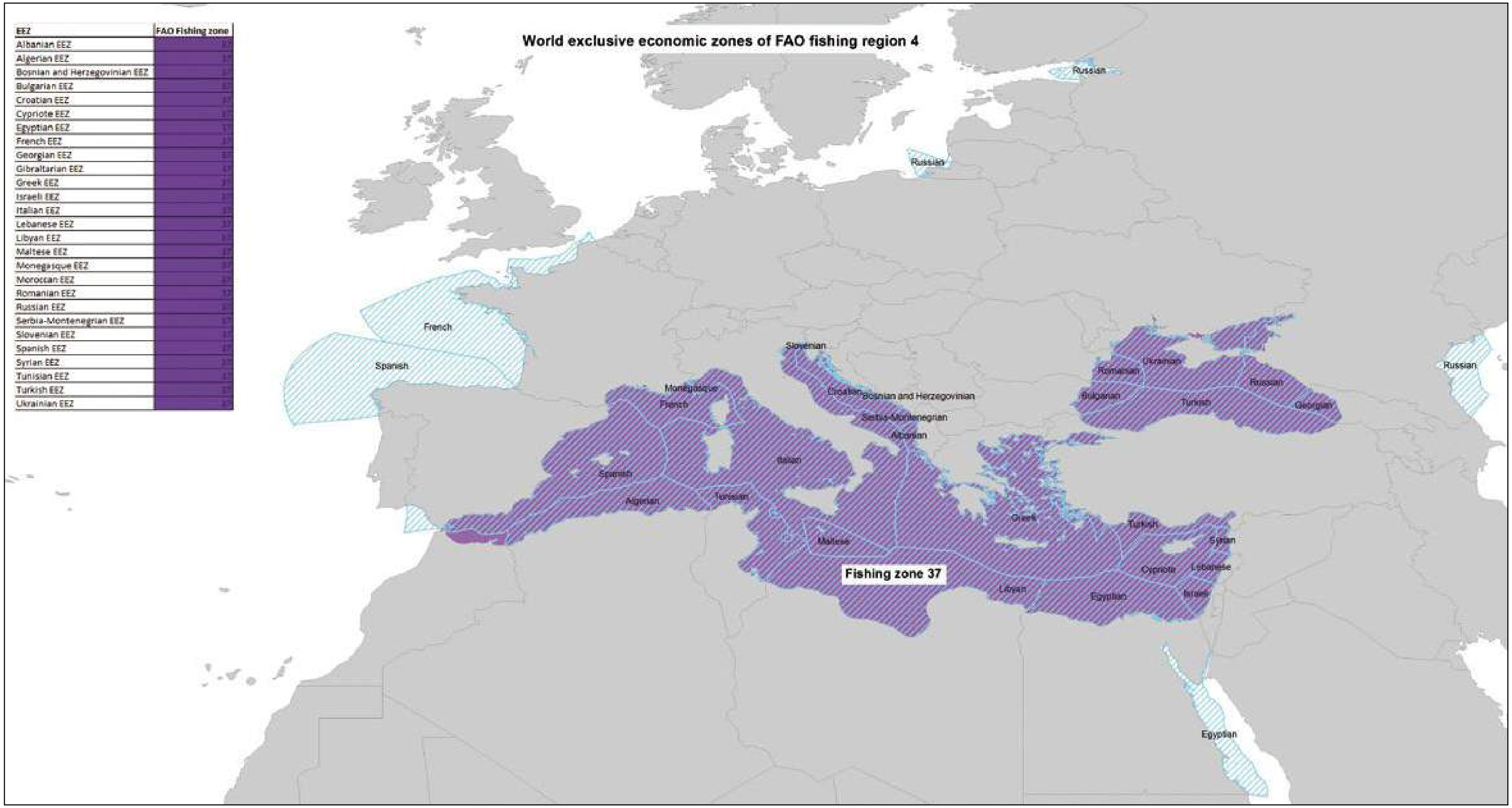
World exclusive economic zones of FAO fishing region 2



EEZ	FAO Fishing zone	EEZ	FAO Fishing zone
Alaskan EEZ	18	French EEZ	27
Canadian EEZ	18	German EEZ	27
Greenlandic EEZ	18	Greenlandic EEZ	27
Russian EEZ	18	Guernsey EEZ	27
Bermudian EEZ	21	Icelandic EEZ	27
Canadian EEZ	21	Irish EEZ	27
Greenlandic EEZ	21	Jan Mayen EEZ	27
Saint-Pierre and Miquelon EEZ	21	Jersey EEZ	27
United States EEZ	21	Latvian EEZ	27
Azores EEZ	27	Lithuanian EEZ	27
Belgian EEZ	27	Madeiran EEZ	27
Bornholm EEZ	27	Norwegian EEZ	27
Danish EEZ	27	Polish EEZ	27
Dutch EEZ	27	Portuguese EEZ	27
Estonian EEZ	27	Russian EEZ	27
Faeroe Islands EEZ	27	Spanish EEZ	27
Finnish EEZ	27	Swedish EEZ	27
		United Kingdom EEZ	27

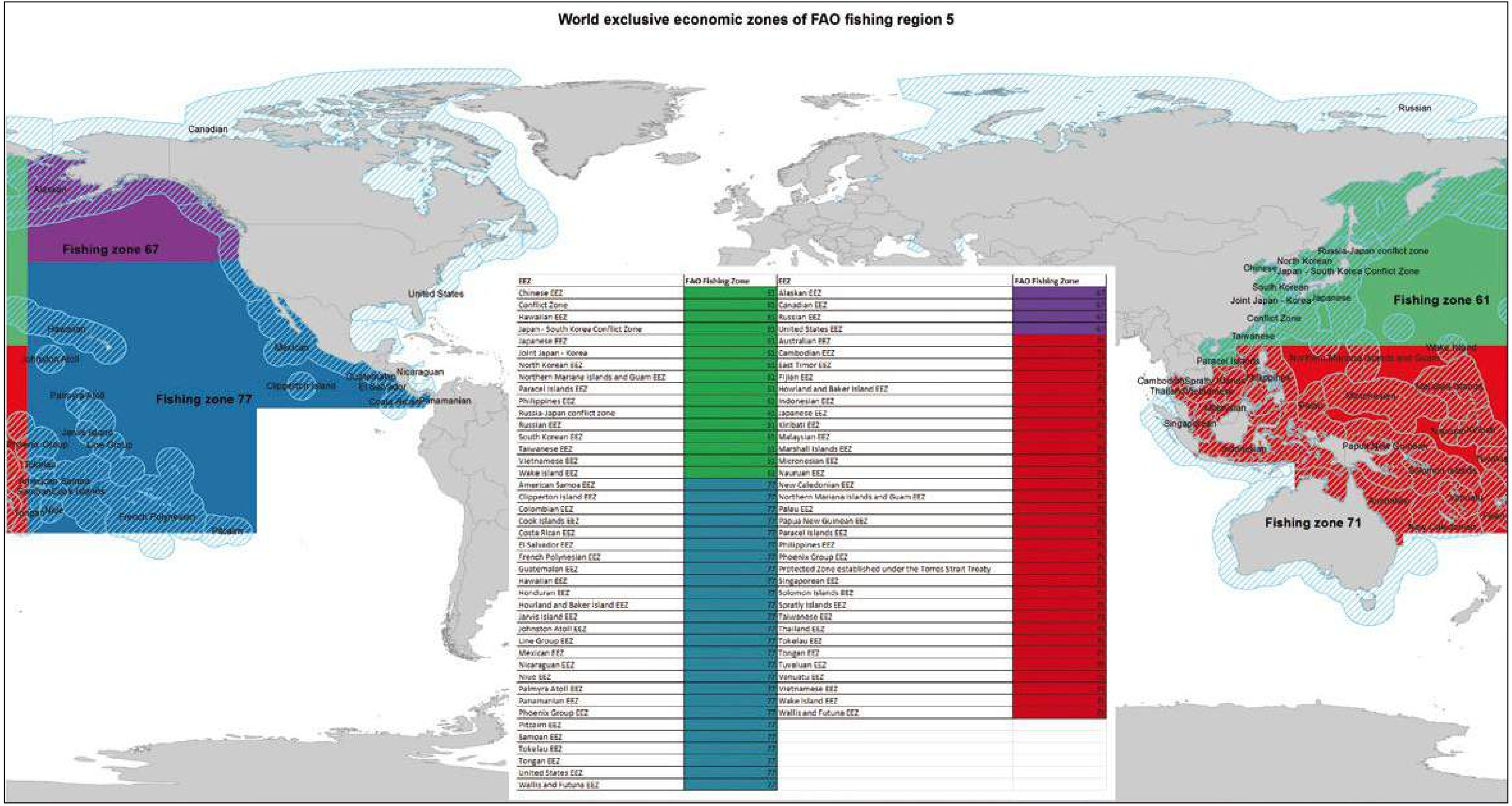


EEZ	FAO Fishing zone	EEZ	FAO Fishing zone
Anguilla EEZ	31	Brazilian EEZ	34
Antigua and Barbuda EEZ	31	Cameroonian EEZ	34
Bahamas EEZ	31	Canary Islands EEZ	34
Barbados EEZ	31	Cape Verdean EEZ	34
Belizean EEZ	31	Congolese EEZ	34
Bermudian EEZ	31	Democratic Republic of the Congo EEZ	34
Brazilian EEZ	31	Equatorial Guinean EEZ	34
British Virgin Islands EEZ	31	Gabonese EEZ	34
Cayman Islands EEZ	31	Gambian EEZ	34
Colombia - Jamaica (Joint Regime)	31	Ghanaian EEZ	34
Colombian EEZ	31	Guinea Bissau EEZ	34
Costa Rican EEZ	31	Guinean EEZ	34
Cuban EEZ	31	Ivory Coast EEZ	34
Dominican EEZ	31	Liberian EEZ	34
Dominican Republic EEZ	31	Madeiran EEZ	34
French Guiana EEZ	31	Mauritanian EEZ	34
Grenadian EEZ	31	Moroccan EEZ	34
Guadeloupe and Martinique EEZ	31	Nigeria - Sao Tome and Principe Joint	34
Guatemalan EEZ	31	Nigerian EEZ	34
Guyanese EEZ	31	Portuguese EEZ	34
Haitian EEZ	31	Sao Tome and Principe EEZ	34
Honduran EEZ	31	Senegalese EEZ	34
Jamaican EEZ	31	Sierra Leonian EEZ	34
Mexican EEZ	31	Spanish EEZ	34
Montserrat EEZ	31	Togolese EEZ	34
Netherlands Antilles EEZ	31	Western Saharan EEZ	34
Nicaraguan EEZ	31	Antarctic 200NM zone beyond the coastline	41
Panamanian EEZ	31	Argentinean EEZ	41
Puerto Rican EEZ	31	Brazilian EEZ	41
Saint Kitts and Nevis EEZ	31	Chilean EEZ (disputed - Peruvian point of view)	41
Saint Lucia EEZ	31	Falkland Islands EEZ	41
Saint Vincent and the Grenadines EEZ	31	French Guiana EEZ	41
Saint-Martin EEZ	31	Trindade EEZ	41
Sint-Maarten EEZ	31	Uruguayan EEZ	41
Surinamese EEZ	31	Angolan EEZ	47
Trinidad and Tobago EEZ	31	Ascension EEZ	47
Turks and Caicos EEZ	31	Congolese EEZ	47
United States EEZ	31	Democratic Republic of the Congo EEZ	47
Venezuelan EEZ	31	Gabonese EEZ	47
Angolan EEZ	34	Namibian EEZ	47
Ascension EEZ	34	South African EEZ	47
Azores EEZ	34	St. Helena EEZ	47
Beninese EEZ	34	Tristan Da Cunha EEZ	47



World exclusive economic zones of FAO fishing region 4

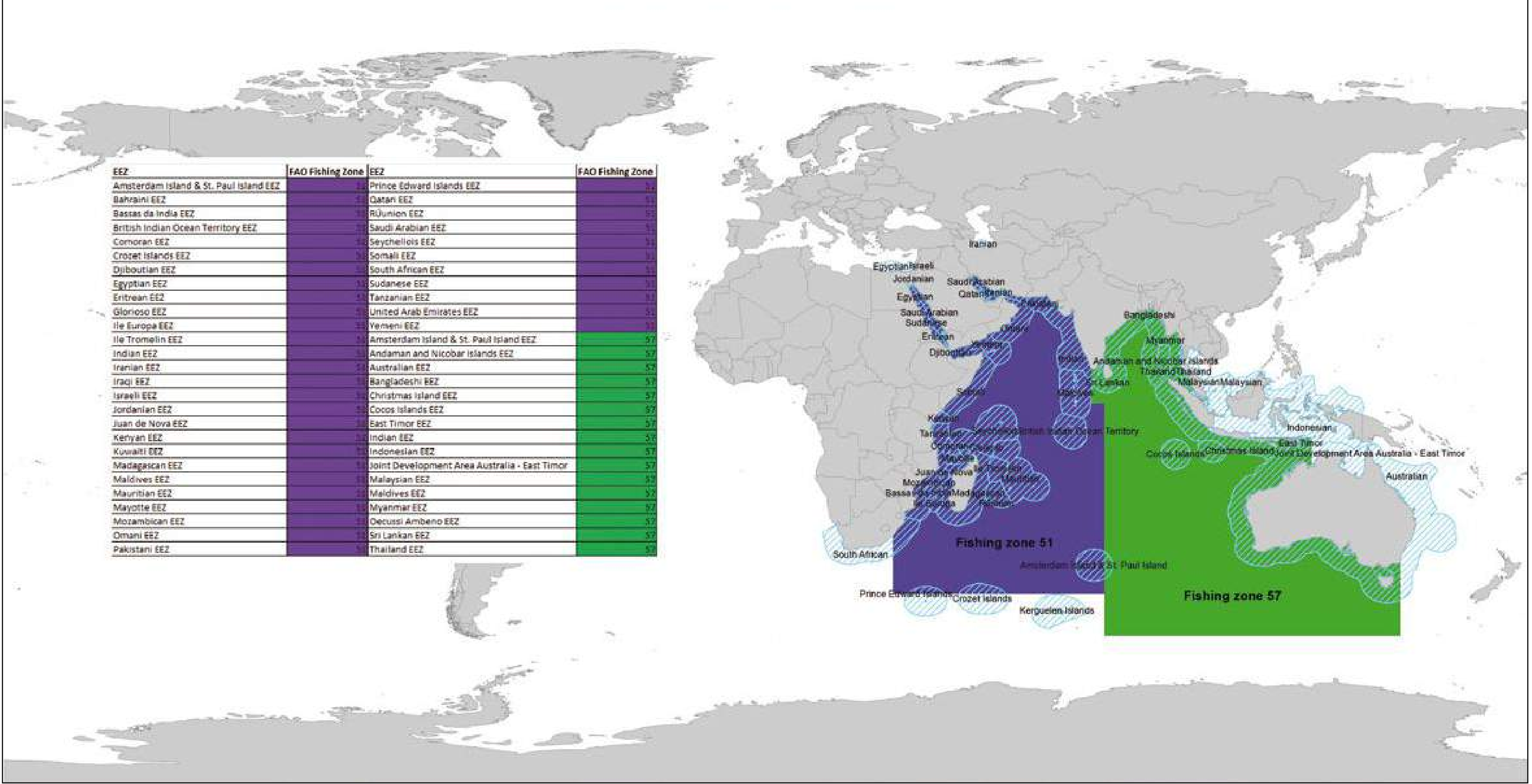
EEZ	FAO Fishing zone
Albanian EEZ	37
Algerian EEZ	37
Bosnian and Herzegovinian EEZ	37
Bulgarian EEZ	37
Croatian EEZ	37
Cypriote EEZ	37
Egyptian EEZ	37
French EEZ	37
Georgian EEZ	37
Gibraltarian EEZ	37
Greek EEZ	37
Israeli EEZ	37
Italian EEZ	37
Lebanese EEZ	37
Libyan EEZ	37
Maltese EEZ	37
Monegasque EEZ	37
Moroccan EEZ	37
Romanian EEZ	37
Russian EEZ	37
Serbia-Montenegrian EEZ	37
Slovenian EEZ	37
Spanish EEZ	37
Syrian EEZ	37
Tunisian EEZ	37
Turkish EEZ	37
Ukrainian EEZ	37



World exclusive economic zones of FAO fishing region 5

EEZ	FAO Fishing Zone	EEZ	FAO Fishing Zone
Chinese EEZ	61	Alaskan EEZ	67
Conflict Zone	61	Canadian EEZ	67
Hawaiian EEZ	61	Russian EEZ	67
Japan - South Korea Conflict Zone	61	United States EEZ	67
Japanese EEZ	61	Australian EEZ	71
Joint Japan - Korea	61	Cambodian EEZ	71
North Korean EEZ	61	East Timor EEZ	71
Northern Mariana Islands and Guam EEZ	61	Fijian EEZ	71
Paracel Islands EEZ	61	Howland and Baker Island EEZ	71
Philippines EEZ	61	Indonesian EEZ	71
Russia-Japan conflict zone	61	Japanese EEZ	71
Russian EEZ	61	Kiribati EEZ	71
South Korean EEZ	61	Malaysian EEZ	71
Taiwanese EEZ	61	Marshall Islands EEZ	71
Vietnamese EEZ	61	Micronesian EEZ	71
Wake Island EEZ	61	Nauruan EEZ	71
American Samoa EEZ	77	New Caledonian EEZ	71
Clipperton Island EEZ	77	Northern Mariana Islands and Guam EEZ	71
Colombian EEZ	77	Palau EEZ	71
Cook Islands EEZ	77	Papua New Guinean EEZ	71
Costa Rican EEZ	77	Paracel Islands EEZ	71
El Salvador EEZ	77	Philippines EEZ	71
French Polynesian EEZ	77	Phoenix Group EEZ	71
Guatemalan EEZ	77	Protected Zone established under the Torres Strait Treaty	71
Hawaiian EEZ	77	Singaporean EEZ	71
Honduran EEZ	77	Solomon Islands EEZ	71
Howland and Baker Island EEZ	77	Spratly Islands EEZ	71
Jarvis Island EEZ	77	Taiwanese EEZ	71
Johnston Atoll EEZ	77	Thailand EEZ	71
Line Group EEZ	77	Tokelau EEZ	71
Mexican EEZ	77	Tongan EEZ	71
Nicaraguan EEZ	77	Tuvaluan EEZ	71
Niue EEZ	77	Vanuatu EEZ	71
Palmyra Atoll EEZ	77	Vietnamese EEZ	71
Panamanian EEZ	77	Wake Island EEZ	71
Phoenix Group EEZ	77	Wallis and Futuna EEZ	71
Pitcairn EEZ	77		
Samoan EEZ	77		
Tokelau EEZ	77		
Tongan EEZ	77		
United States EEZ	77		
Wallis and Futuna EEZ	77		

World exclusive economic zones of FAO fishing region 6



EEZ	FAO Fishing Zone	EEZ	FAO Fishing Zone
Amsterdam Island & St. Paul Island EEZ	51	Prince Edward Islands EEZ	51
Bahraini EEZ	51	Qatari EEZ	51
Bassas da India EEZ	51	RÜunion EEZ	51
British Indian Ocean Territory EEZ	51	Saudi Arabian EEZ	51
Comoran EEZ	51	Seychellois EEZ	51
Crozet Islands EEZ	51	Somali EEZ	51
Djiboutian EEZ	51	South African EEZ	51
Egyptian EEZ	51	Sudanese EEZ	51
Eritrean EEZ	51	Tanzanian EEZ	51
Glorioso EEZ	51	United Arab Emirates EEZ	51
Ile Europa EEZ	51	Yemeni EEZ	51
Ile Tromelin EEZ	51	Amsterdam Island & St. Paul Island EEZ	57
Indian EEZ	51	Andaman and Nicobar Islands EEZ	57
Iranian EEZ	51	Australian EEZ	57
Iraqi EEZ	51	Bangladeshi EEZ	57
Israeli EEZ	51	Christmas Island EEZ	57
Jordanian EEZ	51	Cocos Islands EEZ	57
Juan de Nova EEZ	51	East Timor EEZ	57
Kenyan EEZ	51	Indian EEZ	57
Kuwaiti EEZ	51	Indonesian EEZ	57
Madagascan EEZ	51	Joint Development Area Australia - East Timor	57
Maldives EEZ	51	Malaysian EEZ	57
Mauritian EEZ	51	Maldives EEZ	57
Mayotte EEZ	51	Myanmar EEZ	57
Mozambican EEZ	51	Oecussi Ambeno EEZ	57
Omani EEZ	51	Sri Lankan EEZ	57
Pakistani EEZ	51	Thailand EEZ	57

ANNEX 2:

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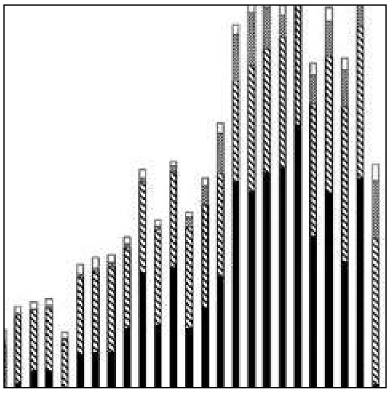

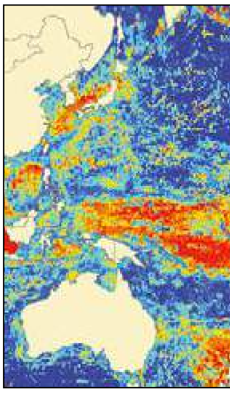

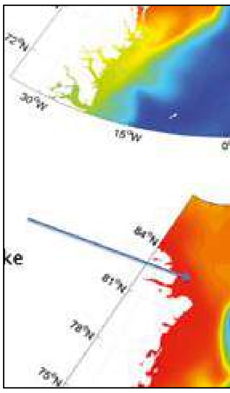

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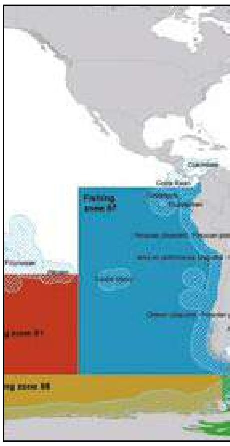

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