ASSESSMENT OF THE RED SEA ECOSYSTEM WITH EMPHASIS ON FISHERIES

by

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Abstract

A comprehensive assessment of the Red Sea large marine ecosystem (LME), with emphasis on fisheries, was carried out using several approaches. The assessment started with a multidisciplinary rapid appraisal of the sustainability of the fisheries using standardized attributes in ecological, economic, social, technical and ethical fields. Then a time-series assessment of the fishery was carried out using data from interviews and the reconstruction of catch from 1950 - 2006. A case study to estimate the unreported catch by quantifying qualitative information on incentives to misreport was carried out for Eritrean fisheries. Finally, a comprehensive and detailed assessment was done in an ecosystem-based framework using the modelling tool Ecopath with Ecosim (EwE), which quantifies the trophic interactions of the organisms and fisheries. It was used to predict the impact of different scenarios of fisheries on the ecosystem and explore the conflict between artisanal and industrial fisheries. Uncertainty analysis was carried out for the different assessment methods employed.

The results of the assessments have varying levels of detail: relative ranking of the sustainability of fisheries in the rapid appraisal assessment, relative quantitative changes over time in the interview analysis, actual historic quantitative assessment of the catches in the catch reconstruction, and finally a quantitative assessment with potential to predict future scenarios using ecosystem modelling. The results give a holistic understanding of the Red Sea ecosystem and its fisheries. The data and resources needed increased as the details of the outputs increased. The assessments complemented each other and there are similarities in the results. They all showed declines in all fisheries, except for beach seining. Sharks, the top predator of the system, showed the worst decline in all the assessments; and the interview and catch reconstruction methods gave strikingly similar results for sharks. The ecosystem modelling did not show direct impact between artisanal and industrial fishery sectors due to the lack of trophic interactions. In addition, the thesis demonstrates that fishery researchers and practitioners can utilize different assessment tools, given the resources at their disposal, to assist the management of resources to conserve ecosystems and livelihoods.

Preface

Some of the chapters of this thesis and the results therein have been published or submitted, or are ready to be submitted. All chapters except 6 are published either fully or partly in peer reviewed journals. Chapter 2 is published: Tesfamichael, D. and Pitcher, T.J. (2006) Multidisciplinary evaluation of the sustainability of Red Sea fisheries using Rapfish. *Fisheries Research* 78: 227-235. It was part of a bigger research project supervised by Dr. Tony J. Pitcher. I was involved in the development of the assessment technique, scored the Red Sea fisheries and provided my scores as test data for the routine developed to do the computation; I also wrote most of the manuscript, which was reviewed and edited by Dr. Tony J. Pitcher. A paper containing parts of Chapter 3 and 4 is published: Tesfamichael, D. and Pauly, D. (2011) Learning from the Past for Future Policy: Approaches to Time-series Catch Data Reconstruction. *Western Indian Ocean J. Mar. Sci.* 10: 99-106. I did the data collection, analysis and writing under the supervision of Dr. Daniel Pauly who also reviewed and edited the manuscript. Chapter 5 is published: Tesfamichael, D. and Pitcher, T.J. (2007) Estimating the Unreported Catch of Eritrean Red Sea Fisheries. *African Journal of Marine Science* 29: 55-63. I did the data collection, analysis and writing under the supervision of Dr. Tony J. Pitcher, who reviewed and edited the manuscript.

Manuscripts submitted include: a paper including part of the results from Chapter 3 and 4. I am a junior author and my contributions include parts of the results and discussion. A second manuscript submitted is one which takes a case study from Chapter 3. Chapter 3 as a whole is ready to be submitted and Chapters 4 and 6 are in preparation to be submitted.

My supervisors: Drs. Daniel Pauly and Tony J. Pitcher, besides the contributions mentioned above in the publications of the papers, were part of the development of the proposals of the chapters of the thesis, supervision during the process, and provided edits and suggestions for improvement of the drafts of each chapter.

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To my loving family

CHAPTER 1: Introduction

1.1 Motivation and development

When I introduce this thesis, I would like to take you for a short tour of my journey in marine science. My first academic encounter with marine sciences started when I joined the Department of Marine Sciences at the University of Asmara, Eritrea where I did my undergraduate degree. Before that, what I remember is the fascination I had with people wearing unusual gear (astronauts and divers) I used to watch on TV and the fish I played with in seasonal lakes near our house. When I began to study marine sciences, the most fascinating part was the field trips I did to the Red Sea coast collecting samples, preparing herbaria, preserving animals, measuring physical and biological parameters, and just being in the sea. A blow to my fascination happened when I learned that I could not dive because I cannot balance pressure due to some problem on my left ear. I was frustrated and depressed because I was not able to fulfil my desire to dive.

When I finished my undergraduate studies, I convinced myself to pay more attention to those areas of marine science which do not require diving for further study and research. The first choice was fishery science. My decision to focus on fishery was not only a reaction to the deflating of my diving fantasy, but also because I enjoyed mathematics, which is a big part of fisheries science and it was my favourite subject in school. So, for my master's degree (MSc) I studied fisheries at Wageningen University, in the Netherlands.

While doing my MSc in the Netherlands, I visited the Fisheries Centre, University of British Columbia and was offered the opportunity to study for PhD. This was a dream come true, because I always wanted to study in some of the best schools in fisheries, of which the Fisheries Centre is one, if not the best. I started taking courses and attending seminars, and soon I started to feel overwhelmed. The kind of research discussed and the amount of data needed seemed something I could not find for the Red Sea. An example of a shocking experience I had is when I volunteered for one weekend in one of the salmon research projects in British Columbia. I joined because I missed going to the ocean on field trips and also wanted to see and learn the local research activities. Although I enjoyed the trip, it shocked me, because microchips that cost more than 200 USD a piece were surgically inserted to salmon fingerlings to estimate their mortality when they migrate down the river to the ocean. I quickly thought how impossible it would be for me to do similar research in the Red Sea simply because it costs a lot of money. I started to hear more about salmon, which I came across in many of the textbooks I used in previous studies, but I never had direct experience of salmon. People talked passionately and romantically about the fascinating life-history of salmon, their migration and jumping over obstacles in streams. However, none of that made a lot of sense to me growing up in a dry area – similar to the many Yemenites in the novel "Salmon fishing in the Yemen" (Torday, 2008). I was familiar with fisheries exploiting groupers, snappers, sharks, emperors and other coral reef fishes of the tropics.

In terms of using fisheries science in sustainable management of fisheries, an even bigger shock came when I started to learn details about the collapse of many fish stocks in Canada, especially the Newfoundland cod. I was puzzled how this could happen in a country with some of the best fishery scientists in the world and how their knowledge was not translated to stop the collapse from happening. This challenged my ambition of 'saving' the fisheries of the Red Sea and helping the poor fishing communities by learning the best science available, and later applying it.

So while sitting in class or thinking about my research, there were moments I felt lost: not necessarily a bad position to be when starting one's research project. When I tried to imagine implementing in the Red Sea what I was learning in classes, I would not go too far. I had many discussions with my supervisors, who were very helpful throughout my study, and finally I decided to do the best I could in learning the different research tools at the Fisheries Centre and apply them to the Red Sea. Thus, I set out to do my research in ecosystem modelling of the Red Sea ecosystem, the new cutting edge tool in fisheries science, which was originally developed for a coral reef ecosystem (Polovina, 1984), the same ecosystem I planned to study. I also wanted to apply other assessment tools to the Red Sea fisheries.

1.2 The rational for fisheries assessment

Because of the vastness of oceans and seas, they were thought, for a long time, to harbor inexhaustible fish and other resources (Costanza, 1999), and that any waste material could be disposed into them without any problem (Sankovitch, 1994). Time and research have proven that both of these ideas were wrong. We have witnessed the collapse or decline of fishery resources globally and pollution threatens many ecosystems. The collapse of Peruvian anchoveta (*Engraulis ringens*) (Boerema and Gulland, 1973); Northern cod (*Gadus morhua*) off the coast of Newfoundland, Canada (Myers *et al.*, 1996); the proportion of large predators declining in the catch (Pauly *et al.*, 1998; Myers and Worm, 2003); the dramatic decline of catches from Southeast Asia (Silvestre and Pauly, 1997; Christensen, 1998) and Western Africa (Kaczynski and Fluharty, 2002) are few examples of the common stories of fisheries almost everywhere. The global catch from marine ecosystems has reached or is beyond maximum biological sustainable limit and cannot be increased further by increasing effort (Watson and Pauly, 2001; FAO, 2005). However, the fishing pressure continues to increase well beyond sustainable levels, notably because of the economic incentives given to fishers in the form of subsidies, without which their activities would not be economically feasible (Sumaila *et al.*, 2010). Thus, a proper assessment of the status of the resources and the level of fishing pressure is a critical starting point to manage the marine resources.

Aquaculture is erroneously perceived to be able to solve some of the problems posed by declining fishery catch, by meeting the increasing demand for seafood. However, except for the planktivore or omnivore fish used by small-scale farms, aquaculture aggravates the problem of fisheries decline as the feed for the most lucrative (and carnivorous) farmed fishes comes from marine ecosystems (Pauly *et al.*, 2002). Discarding of unwanted by-catch is another serious issue in fisheries. Based on data from the late 1980s, global discards were estimated to be 17.9 to 39.5 million tonnes per year, while the (retained) global marine catch given by FAO was around 85 million tonnes in the mid-1990s (Alverson *et al.*, 1994; Zeller and Pauly, 2005). The geographic distribution of illegal, unreported and unregulated (IUU) fisheries are global and because in many cases the benefits of IUU activities exceed the cost of being apprehended, penalties have not been effective deterrent tools (Sumaila *et al.*, 2006). The estimated discarded catch decreased in later years, however, as did the total catch (Zeller and Pauly, 2005). In addition to discards, due attention should also be given to illegal and unregulated fishing (Pitcher *et al.*, 2002).

For centuries, tropical waters were fished by small-scale artisanal fisheries that were more or less in harmony with their environment simply because they did not have the capacity to deplete the resources. They used small, non-motorized crafts, usually sporting sails. Since the colonization of many of the tropical countries, motorization and introduction of bigger fishing vessels became common everywhere, without any adequate monitoring and management programs. This resulted in the destruction of ecosystems and was a threat to the livelihood of small-scale fishers. For example, the productive Gulf of Thailand was fished predominantly by small scale artisanal fisheries until the early 1960s, when trawlers were introduced (Silvestre and Pauly, 1997). Soon after, the catch per unit of effort of the trawlers decreased by an order of magnitude, and the catch composition was greatly altered, toward smaller fishes and invertebrates, notably cephalopods (Christensen, 1998). Nets with very small mesh sizes that are destructive to the ecosystem were used. By 1973, the Gulf of Thailand was considered over-fished (Boonyubol and Pramokechutima, 1984) and in 1980, it was severely depleted (Christensen, 1998). Similar developments occurred in Taiwan and the Saharan Banks off West Africa (Balguerías *et al.*, 2000; Lu, 2002). Fisheries in developing countries are very important globally. They contribute a large proportion to the world catch (Chuenpagdee *et al.*, 2006). In addition, the fact that they employ so many people gives them more social weight (Pauly, 2006).

The decline of fisheries is often attributed to a combination of factors including variation in environmental conditions, the stochastic nature of fish stocks and other factors over which we do not have much control. Human exploitation of the oceans, however, nowadays is the most significant factor in the decline and we can do something about it. Human effects have directly (e.g., fishing) and indirectly (e.g., greenhouse gas emission leading to ocean warming and acidification) affected fishery resources (Cheung *et al.*, 2011). As fisheries or ecosystem services of oceans are not infinite, care should be taken on how to use the resources. This calls for proper management. The general objective of fisheries management is sustainable use of the resources so that future generations will have as fair a chance of using them as the present generation. Fisheries managers need information to know the status of the resource and to monitor the effectiveness of the management strategies. Of course, in the implementation of the management policies, enforcement is key.

Fisheries management and research have focused for many years on the species that are economically important; and estimated their potential and status to decide on the total catch allowed to be fished. The concept of Maximum Sustainable Yield (MSY) has been guiding the management of many failed fisheries, and hence its demise has often been proclaimed (Larkin, 1977), though it keeps inspiring legislation, especially at the international level. A valid point of criticism, however, is that MSY is difficult to apply in an ecosystem context. In addition to the targeted organisms, fishing affects all the organisms which are directly or indirectly connected to the targeted species, i.e., the effects of exploiting one species are felt throughout the ecosystem, and this should be taken into consideration (Hall, 1999). Fishery, as natural resource exploitation, is not only a biological issue, but also socio-economic and political; thus raising issues of public policy (Pauly and Maclean, 2003; Pauly and Zeller, 2003). However, in this complicated system, starting with the assessment of the status of the resources and the fisheries will always be a step in the right direction.

1.3 Thesis outline

The overarching objective of the thesis is to assess the Red Sea ecosystem and the status of its fishery resources, which will be explored in the 5 major chapters (not including the introductory and concluding sections) introduced below**.** I will introduce them in the way they were conceived and developed, rather than in their order in the Table of Contents. The first study I started doing was the ecosystem model of the Red Sea, which is the last Chapter (6) of the thesis in its current format. The objectives of this chapter were first to develop a quantitative description of the ecosystem and the trophic interactions of the organisms, i.e., the flux of energy from one group to another, and second to quantify and evaluate the effect of fisheries on the ecosystem. The model was also to be used to explore different fishing scenarios and if the development of industrial fishery in the Red Sea affects the catch of artisanal fisheries. This has been a cause for some serious conflicts between the two sectors in the Red Sea. Thus, Ecopath with Ecosim (EwE) ecosystem modelling (Christensen *et al.*, 2008) was used to assess the Red Sea in an ecosystem-based framework.

Ecosystem models are very data-hungry, thus I started collecting data. Most of the biological data (e.g., growth and mortality) were acquired from published papers and FishBase (Froese and Pauly, 2012). The first serious practical obstacle was faced when I started looking for fishery catch data from the countries bordering the Red Sea; getting long time series of catches proved to be very difficult. For the Red Sea countries, it was not only a question of whether the fisheries authorities of the country would cooperate or not, but whether such data existed. Using the fishery data the countries reported to the Food and Agricultural Organization (FAO) of the United Nations was considered; however, the reliability of the database was questionable (Pauly and Zeller, 2003). At the same time, the *Sea Around Us* Project, based at the Fisheries Centre, University of British Columbia, was embarking on a project to improve the global fishery catch by 'reconstructing' the catches of each of the world's maritime countries. So reconstructing the Red Sea fishery catch was a logical step to do.

I started familiarizing myself by reviewing the fisheries of the Red Sea countries and evaluating them using a rapid appraisal method called 'Rapfish', Chapter 2 of the thesis details this approach. Rapfish, which stands for 'Rapid Appraisal of Fisheries', is a multidisciplinary technique which evaluates the sustainability status of fisheries based on transparent and semi-quantitative scoring of sets of ecological, economic, social, technological and ethical attributes. It uses a non-parametric statistical ordination technique (multidimensional scaling, MDS) to rank the relative sustainability of fisheries in each field. Thus, the main objective of this chapter is to conduct a comprehensive review of the Red Sea fisheries and evaluate their sustainability.

Once the fisheries were reviewed, searching and collecting materials for data to reconstruct the Red Sea fisheries started. The search started first at the library and borrowing materials through interlibrary loan system of the University of British Columbia from libraries and data repositories in the world. When those sources were exhausted and there were still many gaps, a field trip was planned to the Red Sea to search data sources from local organizations. One source of information to explore during the field trip was the knowledge accumulated in the fishers and local communities who have been depending on the Red Sea resources for their livelihoods for centuries. This became a new chapter for the thesis.

Chapter 3 deals with the use of interviews to capture fishers' knowledge and their perception about the resources and the changes over time. The main objective of this chapter is to quantify the patterns in the fisheries over a long period by interviewing different age groups of fishers, community elders and fishery administrators. The data from the interviews were used to analyze relative changes in catch rates over a long period, and to fill in data gaps, such as unreported catch. This can be done in two ways: first by asking fishers direct quantitative questions about some parts of the catch that never get reported, e.g., the amount of fish consumed by the crew, and given to family and friends, or by asking fishers to give qualitative information about periods where catch data was not readily available. Interviews were also used to double-check conflicting data in reports.

With all the possible data sources acquired, the catch reconstruction of the Red Sea fisheries is carried out in Chapter 4. The main objective of this chapter is to reconstruct a set of comprehensive and standardized catch data for the Red Sea fisheries from 1950 – 2006, the most recent data available during the research. This will help to understand the development of the fisheries over time, identify major shifts in effort and target species, and will form the basis for any subsequent quantitative analysis to be carried out on the fisheries sector. The catch reconstruction was done by taxonomic composition of the catch for each type of fishing gear.

Chapter 5 looks at estimating the unreported catch using qualitative information about events or situations that can potentially influence fishers to misreport. Although their presence is not debated, unreported catches, as the name indicates, are not available in official fishery statistics. However, information, mainly qualitative, is usually available either in reports or from the experts in the field about events that happened in the history of the fisheries that could affect the incentives to misreport catch. The main objective of this chapter is to quantify the unreported catch based on those qualitative clues. This case study was done for Eritrea, my home country, where I had better access to documents and people involved in fisheries. This chapter also demonstrates uncertainty analysis in estimating the unreported catch. All the information from

Chapters 2 – 5 are used in the ecosystem based assessment of the Red Sea (Chapter 6). These chapters are written as papers able to be published independent of the other chapters and some of them are already published. Hence, some facts about the Red Sea may be repeated.

1.4 The Red Sea

In the next few pages, the Red Sea ecosystem and the countries bordering the Red Sea are briefly introduced. The Red Sea is an elongated narrow sea between Northeastern Africa and the Arabian Peninsula, ranging from 30^0N to $12^0$30'N with a total length of 2000 km, and from 32^0E to 43^0E with an average width of 208 km (Figure 1.1). The maximum width is 354 km in the southern part (Morcos, 1970). The total area is 4.51 x 10^5 km^2. It is connected with the Indian Ocean in the south through a small strait of Bab al Mandab, meaning door of fortune, which is only 29 km wide. Bal al Mandab has a sill, 137 m below sea level, which limits the circulation of water between the Red Sea and the Gulf of Aden. The Red Sea is also connected to the Mediterranean Sea through the Suez Canal since its opening in 1869. The average depth is 491 m and the maximum recorded is 2850 m. In the north, the Red Sea is divided into the Gulf of Suez and Aqaba. The Gulf of Suez is generally wide, shallow and muddy, while the Gulf of Aqaba is narrow and deep.

Geological evolution

The Red Sea is formed by the divergence of the African and the Arabian plates. It is part of a larger rift system that includes the Dead Sea and the East African rift systems. Geologically it is categorized as a young ocean and is still growing or spreading (Braithwaite, 1987). The zone was already structurally weak during the Pan-African orogeny 600 Ma. The split of the Arabian and African plates is believed to have started in the Tertiary period between the Eocene and Oligocene periods and it accelerated during the late Oligocene with intense magmatic activity and the development of a continental rift (Makris and Rihm, 1991). It was formed as an embayment due to the expansion of the Mediterranean Sea. The Red Sea depression is believed to have been flooded by the Mediterranean as a result of extensive sinking in the early Miocene

(Girdler and Southren, 1987). Since the starting of its formation, the Red Sea went through a series of connection and disconnection with the Mediterranean in the North and Indian Ocean in

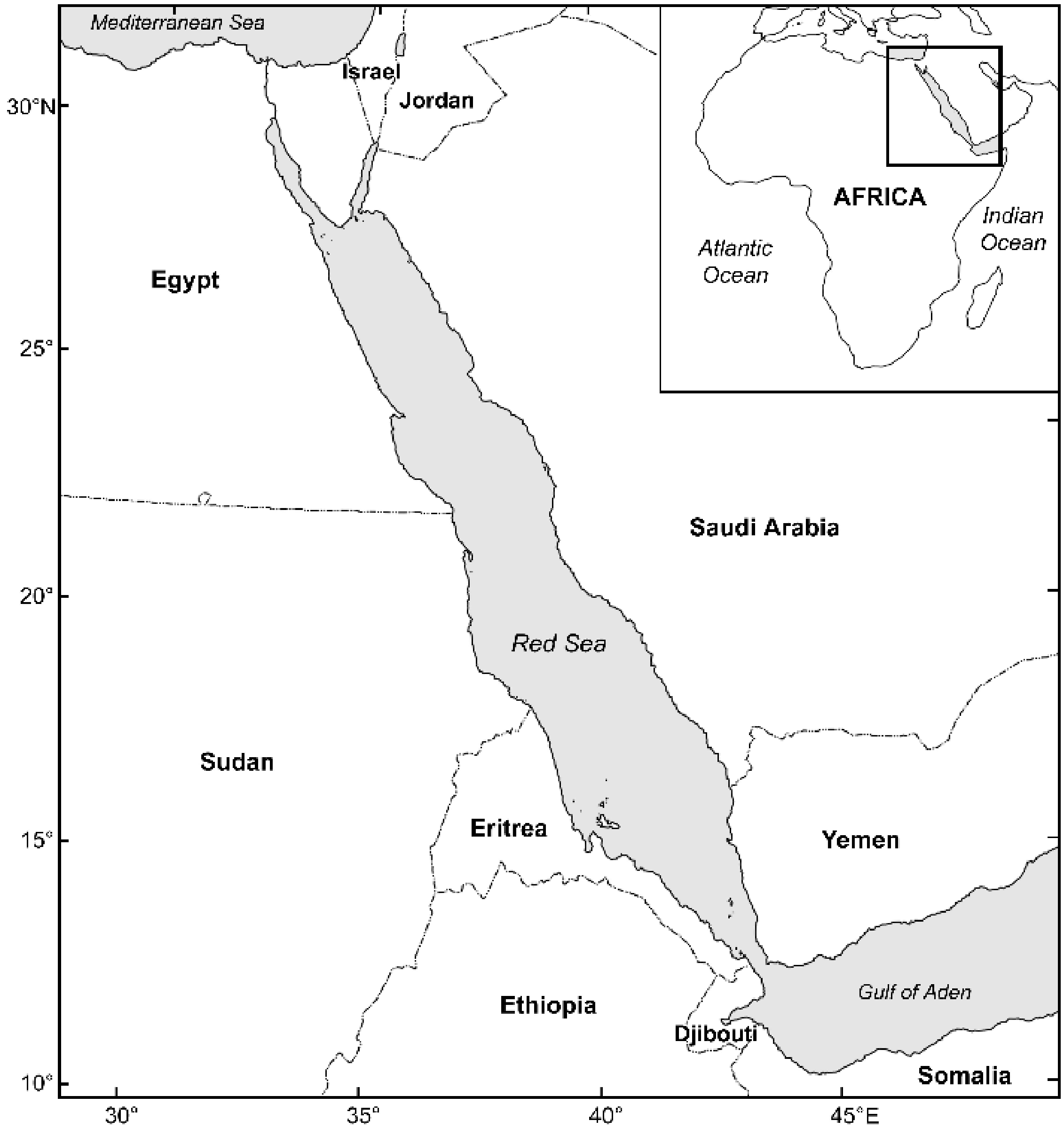


Figure 1.1 The Red Sea and the bordering countries.

the south. At the end of Miocene, upheaval of land occurred and the Red Sea was disconnected from the Mediterranean to become a separated salty lake. At the beginning of the Pliocene, the Red Sea was reconnected with the Mediterranean and for the first time it was connected with the Indian Ocean. At the end of Pliocene, only the northern connection with the Mediterranean was closed off due to crustal plate movement. Later the connection with the Indian Ocean was closed off during the Pleistocene, the glacial period, when the Red Sea became an isolated sea again. At the end of the glacial period, its connection with the Indian Ocean was re-established, whereas the connection with the Mediterranean remained closed until it was artificially opened via the Suez Canal in 1869 (Goren, 1986; Getahun, 1998). The Red Sea being young and still expanding is used as a case study to understand and explain plate tectonics, mid ocean ridges and formation of oceans.

Origin of biota

The connections of the Red Sea with its neighbouring waters explain the kind of species it was colonized by at different times. Though the Red Sea was first populated by Mediterranean species, its current biota resembles more that of the Indian Ocean. When the Red Sea was disconnected with Mediterranean and for the first time connected with the Indian Ocean in the beginning of the Pliocene period (about 5 – 6 million years ago), it was populated by Indian Ocean fauna. Later during the glacial period of the Pleistocene, the level of the world's oceans was low. The Red Sea was isolated with high level of salinity (about 50 psu at the surface) and low temperature (about 2^0C lower than the present) (Thunell *et al.*, 1988). This resulted in the massive extinction of many species. Then later, when it was reconnected with the Indian Ocean at the end of the glacial period, 10 – 12 thousand years ago, it created an opportunity for the Indian Ocean species to re-populate the Red Sea (Goren, 1986).

Physical oceanography

The Red Sea area is generally arid, rainfall is very sparse with annual average ranging from 1 mm – 180 mm (Edwards, 1987). Evaporation, with annual average of 2 m (Morcos, 1970), exceeds precipitation. The deficiency is made up by the flow of water from the Indian Ocean through Bab al Mandab. The water flows over a sill which is 137 m below the sea level. In winter, warmer and less saline water flows into the Red Sea in the surface layer; while cooler and saltier water flows into the Gulf of Aden in the lower layer. In summer, there are three layers of water flow in the strait. In addition to the two flows of winter, warm water flows on the surface from the Red Sea to the Gulf of Aden (Smeed, 2004). Sea and air temperatures are high in the Red Sea with mean annual sea surface temperature of 28^{o}C. Another remarkable characteristics of the Red Sea is its high salinity, about 35 psu on average at the surface; readings as high as 40.5 psu are also reported. The high salinity is due to a combination of its geological history and its location in dry and hot environment. Though originally the Red Sea depression was flooded with Mediterranean water, it soon started to become more saline due to high evaporation. Later during the glacial period, the Red Sea was an isolated salty lake with salinity higher than the present by a value of 10. The highly saline water was diluted by water from Indian Ocean when the Red Sea was reconnected with the Indian Ocean (Thunell *et al.*, 1988). However, it is still more saline than the Indian Ocean water due to high evaporation (Morcos, 1970).

Biological oceanography

The Red Sea is not very productive, mainly due to lack of nutrient-rich terrestrial run off; also, there is no circulation of the nutrient rich deep water to the surface where photosynthesis takes place. The vertical mixing of water is prevented by a permanent thermocline as the temperature of the sub-surface water is always lower than the warm surface temperature. The depth of the thermocline is deeper in winter than summer (Edwards, 1987). Generally, the southern part of the Red Sea is more productive than the northern part due to the flow of nutrient rich water from the Indian Ocean, the main nutrient input, and the re-suspension of nutrients from the bottom sediments by turbulent mixing from its broad and shallow shelf area (Sheppard *et al.*, 1992)**.** The shallow water of the Gulf of Suez is also productive and supports many exploited fish populations.

The high and relatively stable temperature of the Red Sea is favourable for the formation of coral reefs. They are more developed in the northern part starting from the tip of Sinai Peninsula going south parallel to the coast. The longest continuous fringing reef in the Red Sea extends from Gubal (at the mouth of the Gulf of Suez) to Halaib, at the Egyptian border with Sudan (Pilcher and Alsuhaibany, 2000). In the south, more patchy reefs are observed as the turbid water of the shallow shelf does not allow the formation of extensive reefs. Sanganeb Atoll, located in Sudan near the border with Egypt, is the only atoll in the Red Sea. It is unique reef rising from 800 m depth to form an atoll that has been recognized as regionally important conservation area. It was proposed to UNESCO for World Heritage Status in the 1980s (Pilcher and Alsuhaibany, 2000). Coral reefs have a self-sustained nutrient cycle and have high productivity, much like an oasis in a desert. They attract fisheries, mainly small-scale artisanal, and tourists.

The Red Sea has very high diversity, more than 1200 species of fishes are reported (Froese and Pauly, 2011). It is also characterized by high degree of endemism. Some research put the percentage of Red Sea endemic fishes between 10 - 17% (Ormond and Edwards, 1987); its semi-closed nature and unique ecological conditions contribute to this high number. Because the Red Sea has very low nutrient input, species that can survive its environment have very good chance to dominate as there are fewer competitors. One good example is the phytoplankton *Trichodesmium erythraeum*. It is a blue green alga (cynobacterium) that can overcome nitrate depletion by fixing atmospheric nitrogen dissolved in the water. In calm waters the filaments of the blue green algae float to the sea surface and form a rather reddish scum, probably the origin of the name Red Sea.

On the shores of coastal lagoons and sheltered bays mangroves are common. The most common species is *Avicennia marina. Bruguiera gymnorhiza* and *Ceriops tagal* also occur, though they are less common. The shallow waters of the lagoons and bays are home to sea grass beds. About 500 species of algae are reported from the Red Sea. Most algae in the north and central part are macroscopic, non-calcareous, brown, green and red algae. In the south, large brown algae such as *Sargassum* dominate (Walker, 1987).

Five sea turtle species are reported from the Red Sea: Hawksbill, Green, Oliver Ridley, Loggerhead and Leatherback. Hawksbill and Green turtles are the most common and are reported to nest in the Red Sea (Frazier *et al.*, 1987). There is no active hunting for sea turtles in the Red Sea. However, they are accidentally caught in fishing nets. The rich seagrass beds support dugongs. They are reported from Gulf of Suez in the north and the coast of Sudan and the Dahlak Archipelago in Eritrea (Preen, 1989). The reports of Cetaceans from the Red Sea are sparse. Seven species of dolphins are commonly reported. Occasional spotting of Killer whale and False killer whale are also reported. Frazier *et al.,* (1987) suggested that the narrow strait of Bab al Mandab and the low productivity in the Red Sea as reasons for the low population of cetaceans. As far as seabirds are concerned, the enclosed nature of the Red Sea acts as a barrier for pelagic fishes on which many birds feed. As a result pelagic seabirds, such as shearwaters and petrels, are poorly represented. Because of its elongated shape, the Red Sea has high coast to sea area ratio and its seabird fauna is dominated by coastal species (Evans, 1987). It is also a migratory route for many birds.

Human aspects

According to archeological evidence, human settlement on the Red Sea coast started centuries ago (Horton, 1987) and the Red Sea has the oldest archeological records of human use of marine resources based on the middens of giant clams and others shells (Walter *et al.*, 2000). It was used as an important trade route between the Indian Ocean and the Mediterranean. To date, in contrast with the rest of the world, where most of the population lives in a narrow strip of land along the coast (Edgren, 1993), the population density on the Red Sea coast is still very low, except for very few major ports and cities. This is mainly due to the arid and hot climate and as a result most of the settlements have been farther inland in milder climate, where there are enough fresh water supplies. This has greatly limited the degree of coastal shoreline alteration, pollution and resource abstraction. The local traditional societies depend on harvesting marine resources for subsistence using traditional methods of shell collection and fishing. However, in the last few decades, the wider availability of technology coupled with cheaper oil, at least for the oil producing countries, is changing the demography of the Red Sea coast. The major port cities are metropolitan, with diverse economic activities where trades other than fishing are common. Egypt has a strong recreational and tourism industry, and its coast is quite populated, creating pressure on the coastal ecosystems. Air conditioners and desalination plants are making life easier. A typical example is the Saudi Arabia coast where exciting cities, such as Jeddah, have grown fast and new cities (e.g., Yanbu) are developing. In such cities, reclamation and dredging are becoming common for residential, commercial and industrial purposes. Pollution is prevalent around urban areas and ports. Lack of sewage treatment is a serious problem throughout the Red Sea damaging ecosystems. The major industries along the Red Sea coast are refineries. Overall the impact of human activities is growing (Frihy *et al.*, 1996).

Research expeditions

One of the earliest scientific expeditions to the Red Sea is the Danish *Arabia Felix* of 1761 – 1767, which spent October 1762 – August 1763 in the Red Sea area. It included the Swedish naturalist Peter Forsskål, a student of Linnaeus, who made an extensive collection of plants and animals, and particularly fish. The report was later published posthumously by Carsten Niebuhr, the sole survivor, in 1775 (Forsskål, 1775). There were many fragmented records of expeditions, most of them unsuccessful, to the Red Sea in the 18th and 19th centuries. One important and outstanding work in describing the Red Sea ecosystem and its organisms is that of Carl Benjamin Klunzinger, a German medical doctor who worked as a quarantine inspector in the Egyptian Red Sea port of Qusier from 1863 – 1869 and 1872 – 1875. His descriptions include coral fauna, fish, Crustacea, hemichordates and meteorological observations (Klunzinger, 1870, 1872), and the culture of the society (Klunzinger, 1878). An Austrian research vessel *Pola* conducted an expedition in 1895 – 1896 to the northern Red Sea (Luksch, 1898) and 1897 – 1898 to the south (Luksch, 1900). It conducted the first oceanographic studies and sampling the deep sea life up to 2000 m (Head, 1987b). The specimens from the expedition are kept in the Natural History Museum in Vienna (Stagl *et al.*, 1996). The more recent expeditions include the *John Murray* expedition carried out using the Egyptian research vessel *Mabahiss* 1933 – 1934 (Tesfamichael, 2005). It collected oceanographic and biological samples throughout the Red Sea and the Arabian Sea. The report is written by Norman (1939) and samples are stored at British Natural History Museum (see Tesfamichael, 2005). From 1959 – 1964 the International Indian Ocean Expedition brought some vessels to sample the Red Sea. The oceanographic data was reviewed and report compiled by Morcos (1970). An Israeli expedition to the southern Red Sea in 1962 and 1965 (Ben-Tuvia, 1968), and the Israeli Marine Biological Station at Eilat which was opened in 1968, also contributed to the knowledge of the Red Sea.

Resource use

The Red Sea has multiple uses, the main one being as a route from the Indian Ocean to Europe. As far as resource extraction is concerned, fishery is the main one. Recently, interest in the tourism industry has been increasing. Egypt has a well developed marine tourism industry along its northern coast. Historically, fishing has been an important economic activity for the coastal population. The traditional artisanal fisheries, which account for 70% of the total landing (52,700t/year) (Sheppard, 2000), have been generally in harmony with the ecosystem because of low population; non-destructive traditional fishing technology; and poor communication and infrastructure. However, recently, more advanced and destructive methods are being used. At the present, fishing operations in the Red Sea range from foot fishermen, who fish mainly for their own consumption, to very large trawlers with freezing facilities. The fisheries in the Red Sea are typical tropical fisheries, multi-gear and multi-species. Most of the fishery is done with wooden boats of size range between 5 – 18 meters, locally called 'Sambuk' and 'Houris'. Sambuks are bigger in size and have inboard engines. Houris are smaller and use outboard engines. Both Sambuks and Houris use similar fishing gears. The most commonly used gears are handlining and gillnet. The main difference in the operation of Sambuk and Houri are length of the fishing trip, crew size and capacity.

The total annual potential landing from the Red Sea was estimated to be 360,000 t (Gulland, 1971). Though the Red Sea accounts for 0.12% of the total world ocean area, its contribution to the world catch is only 0.07% (Head, 1987c). Nevertheless, it is significant to the countries in the region. Fishery produces a cheap source of protein and provides livelihood for the communities on the coast. Since the countries on the Red Sea coast are generally less industrialized, fisheries can be a good source of employment.

Of the seven countries that border the Red Sea, Jordan and Israel have too small coastlines to support any major fishery. Of the other countries, Egypt and Yemen have well established fisheries and have been utilizing their resource for a long time. Egyptian and Yemen fishermen also fish in other countries' waters. Sudan and Eritrea are the countries which utilize their fisheries resources the least. Saudi Arabia has recently established an industrial fishery, in addition to the artisanal fishery that has been active for many years.

1.5 The Red Sea countries

Seven countries border the Red Sea. These are (counter clockwise): Egypt, Sudan, Eritrea, Yemen, Saudi Arabia, Jordan and Israel (Figure 1.1). The access Jordan and Israel have to the Red Sea is through a small strip of coast in the Gulf of Aqaba. Yemen, Egypt, Saudi Arabia and Israel have also coastlines outside of the Red Sea, which posed some problems with their fisheries catch data, particularly in the case of Yemen and Saudi Arabia (see below).

Egypt

Egypt has access to both the Mediterranean Sea and the Red Sea. The catch from the Mediterranean Sea is slightly higher than from the Red Sea. Most of the Egyptian fishery in the Red Sea is in the shallow waters of the Gulf of Suez, which is favorable for purse seining and trawling. The continental shelf area of the Gulf of Suez (8,400 km^2) is equivalent to the continental shelf of Egypt in the rest of the Red Sea. Foul Bay, in the south close to the border with Sudan, is also an important fishing ground. Purse seining, which accounts for more than 50% of the total catch, is carried out at night using lighted dinghies to attract fish (Sanders and Morgan, 1989); the main landings from this gear are horse mackerel and scads (Carangidae). The second most important fishery is trawling. It operates from September to May and its catch is dominated by lizardfish (Synodontidae), snappers (Lutjanidae) and threadfin breams (Nemipteridae). The prime target of trawlers is shrimp, which accounts for around 10% of the total catch. Reef associated artisanal fisheries contribute only a little to the total catch. They use handlines, longlines and to lesser extent gillnets and trammel nets. Egyptian fishery is the most industrialized in the Red Sea and the Egyptian coast is the most exploited. The Gulf of Suez is believed to be over-fished (Hariri *et al.*, 2000). The number of motorized boats decreased since the mid of 1990s, but the total power more than doubled in order to fish in more distant areas (PERSGA, 2004).

Sudan

The main fishery along the Sudanese coast is handlining, representing 80% of the total catch (Hariri *et al.*, 2000). The most productive areas are the inner edges of the offshore coral reefs which are 5 – 10 km from the shore. The species dominant in the catch are groupers (Serranidae), emperors (Lethrinidae) and snappers (Lutjanidae). Pelagic species including Spanish mackerel, barracuda, trevallies and jacks are caught by trolling to and from the fishing grounds (Kedidi, 1984). Small boats are used closer to the shore and the larger motorized boats are used further offshore. Gillnet is used in areas very close to the landing sites. The catch tripled from 1975 – 1984, but started to decrease steadily because projects helping the artisanal fishery phased out, production cost increased and credits given from the Agricultural Bank of Sudan were too expensive (PERSGA, 2004). Industrial fishery is under-developed in Sudan (Hariri *et al.*, 2000). A few trawlers operate in Sudanese water off the Tokar delta, in the south, for shrimp. There is also purse seine fishery in the north, mainly in Foul Bay. An important fishery for trochus shell (*Trochus dentatus*) and black mother-of-pearl shell (*Pinctata margaritifera*) exists in Sudan. The main fishing ground is Danganab Bay. Shells are collected by free diving.

Eritrea

The Eritrean fishery was at its peak in the 1950s and 1960s and was dominated by beach seine targeting small pelagic species, mainly sardine *(Herklotsichthys quadrimaculatus*) and anchovies (*Encrasicholina heteroloba* and *Thryssa baelama)* (Grofit, 1971). They were converted to fish meal to be sold in Europe and sun dried for human consumption markets in Asia. Off-shore trawlers fishing for lizard fish and threadfin bream and inshore trawlers for shrimp were also active. The industry was rendered close to non-existent by war in the 1970s and 1980s, leaving only the reef-based fishery. After the war had stopped in 1991, the fishery was restructured and the catches started to increase steadily. For the first few years, it was almost exclusively dominated by artisanal fisheries which operate around coral reefs using handlining, and gillnets. Later, larger commercial trawlers, chartered from other countries (mainly Egypt), were introduced to target shrimp and fish. A local industrial fishery using longline, which targets coral reef fishes, and pelagic species near coral reefs, is also present.

Yemen

Fishery catches in the Gulf of Aden are higher than catches from the Red Sea for Yemen. However, of the countries in the Red Sea, Yemen has the largest catch, which can be attributed to the productive waters of the southern Red Sea and the large size of the fishing industry (Hariri *et al.*, 2000). While the catch from Gulf of Aden is decreasing, that of the Red Sea is increasing. The Red Sea fishery is dominated by artisanal fisheries ranging from small non-mechanized to relatively larger (10 – 15 m) boats with inboard engines. More than 90% of the total landing is by artisanal fisheries (PERSGA, 2004). Some of the boats are used to trawl for shrimp, mainly *Penaeus semisulcatus*. The gear most used for fish are drift net and handline (Hariri *et al.*, 2000). Indian mackerel, king fish, jacks, emperor, barracuda and shark are dominant in the catch. Extensive subsidies made fishery very profitable and allowed dramatic expansion even to the waters of neighboring countries (Sheppard, 2000). The industrial trawlers in Yemen target demersal fishes, mainly shrimp; there are foreign joint venture companies involved (Hariri *et al.*, 2000).

Saudi Arabia

Saudi Arabia has access to both the Red Sea and the Persian Gulf. More than 50% of its marine catch comes from the Red Sea. There is more potential in the Red Sea than the Persian Gulf, which is fished intensively. Saudi Arabia has a high population density on the coast compared to other Red Sea countries; as a result there are many fishing villages. Fish landings per unit of area increases from north to south (PERSGA, 2004). Artisanal fishery was the only fishery operating in the Red Sea coast of Saudi Arabia until 1981, when trawlers were introduced to fish shrimp. Since then, the catch of trawlers has increased significantly. At the same time, the artisanal gillnet fishery expanded dramatically, with the introduction of fiber glass vessels accounting for the major share of the landing (Sanders and Morgan, 1989). The artisanal catch is almost equally divided between pelagic and benthic species associated with coral reefs; in the northern part it is dominated by mackerels and jacks whereas in the south it is mullets (Mullidae), groupers (Serranidae) and snappers (Lutjanidae). The inner passages around Frasan Bank and Gizan are the main trawling grounds (Hariri *et al.*, 2000).

Jordan and Israel

Jordan and Israel have very small coast in the Gulf of Aqaba, and neither country has a major fishery along its Red Sea coast. Israel used to fish in the southern Red Sea off the coast of Eritrea, mainly in the 1950s and 1960s (Ben-Yami, 1964; Grofit, 1971). Israel has access to the Mediterranean Sea, while Jordan's only marine access is to the Red Sea.

CHAPTER 2: Multidisciplinary assessment of the sustainability of Red Sea fisheries using Rapfish

2.1 Synopsis

A multidisciplinary comparative evaluation of the “health” or sustainability status of 26 major Red Sea fisheries from 5 countries was performed using 44 scored attributes in ecological, economic, social, technological and ethical fields. A multidimensional scaling (MDS) technique (“Rapfish”) was employed to visualize the status of the fisheries for each evaluation field. Comparisons were made among the countries bordering the Red Sea coast, between artisanal and industrial fisheries, and between west and east coast fisheries. Monte Carlo sampling simulation was used to analyze uncertainty. Leverage analysis examined the sensitivity of status results to each attribute in the five evaluation fields. Lack of reliable fisheries stock assessment data is not unusual in many tropical countries; however, this chapter demonstrates that the approximate relative status of fisheries can be obtained using attributes which are relatively easy to score in a transparent fashion with defined uncertainty.

2.2 Introduction

There is little published information on the status of fisheries in the Red Sea, a sea almost enclosed at both ends with little water exchange with neighbouring water bodies. This chapter employs a transparent semi-quantitative multi-disciplinary evaluation method (Pitcher and Preikshot, 2001), in order to provide a preliminary assessment of the sustainability status of the major fisheries in the Red Sea.

Seven countries border the Red Sea, namely Egypt, Sudan, Eritrea, Yemen, Saudi Arabia, Jordan and Israel (Figure 1.1). The Red Sea coasts of Jordan and Israel are too small to support any major fisheries, and they are not considered here. Of the other five countries, Egypt and Yemen have long-established domestic Red Sea fisheries, and they both fish in other countries' waters. Saudi Arabia has recently established an industrial fishery and an artisanal fishery has been operating for many years. Sudan and Eritrea are the countries which utilize their Red Sea fisheries resources the least.

The Red Sea has low productivity on account of its situation in an arid region with no major river inflows. In addition, the presence of a permanent thermocline inhibits benthic nutrients from circulating to the surface where most primary production occurs (Edwards, 1987). The main nutrient input is from the Indian ocean through the southern part of the Red Sea (Sheppard *et al.*, 1992). However, the coral reefs in the Red Sea support an array of organisms. Though the Red Sea accounts for 0.123% of the total world ocean area, its contribution to the world fish catch is only 0.07% (Head, 1987c). Nevertheless, it has fish resources that are significant to the countries in the region, providing a good source of protein and livelihood for the communities on the coast. Since Red Sea countries are generally less industrialized, fisheries can also provide useful employment.

Sanders and Morgan (1989) reviewed Red Sea fisheries and described the resources and stock assessment results for some of the commercially important fish. Head (1987c) gives a brief description of the Red Sea fisheries. Fishing operations in the Red Sea range from foot fishers, without a boat, who fish in the shallow coastal waters mainly for their own consumption, to very large trawlers with freezing facilities. Recently Saudi Arabia has the most advanced fleets and covers a wider fishing area in the Red Sea. The fishery in the Red Sea is a typical tropical fishery, multi gear and multi species, which is done using wooden boats between 5 – 18 meters in size. The most commonly-used gears are handlines and gillnets, operated from large "Sambuks", which have inboard engines, and small "Houris", which use outboard engines. The main differences in the operation of Sambuk and Houri are the length of the fishing trip, crew size and capacity. Fishers tend to concentrate their effort in the coral reef areas, especially artisanal fishers as they do not have powerful vessels to go far from the shore. There are some reports of conflict between the artisanal and industrial fisheries and most of the countries have rules which prohibit industrial vessels from fishing close to the shore. Nevertheless, because of lack of enforcement, they are frequently reported operating in the shallow inshore waters.

Red Sea fisheries are data poor, so conventional stock assessment may only be performed for a minority of species. Moreover, biological assessment alone is not adequate for proactive fishery management and the multidisciplinary nature of fisheries demands a multidisciplinary approach in management and policy making (Salz and De Wilde, 1996). "Rapfish", which stands for Rapid Appraisal of Fisheries, is a novel multidisciplinary technique which evaluates the sustainability status of fisheries based on the transparent and semi-quantitative scoring of sets of ecological, economic, social, technological and ethical attributes. The general definition of sustainability is based on the Oxford English Dictionary "Capable of being maintained at a certain rate or level ... for a long time or indefinitely". Scores in each evaluation field of "Rapfish" are therefore related to the sustainability of the exploited fish populations and their ecosystem. Each fishery is scored for the standardized attributes in each of the five fields. All the fields have 9 attributes each, except ethical that has 8 (Table A.1). Then the scores are converted into relative ranks of the fisheries in two dimensional graphs using the statistical method multidimensional scaling (MDS). MDS uses a non-parametric ordination technique to calculate, from multiple scores of attributes, to provide values that indicate the relative sustainability of fisheries in relation to some fixed extremes in one axis. The technique of Rapfish is thoroughly described by Pitcher (1999) and Pitcher and Preikshot (2001), and its statistical basis by Alder *et al.,* (2000) and Kavanagh and Pitcher (2004). Rapfish does not require quantities of biomass or effort data, which is usually expensive and difficult to obtain in countries with limited resources for fisheries research, but instead relies on easily-obtained indicators or expert opinion with defined uncertainties in scores. Rapfish provides a rapid assessment as to the "heath" or sustainability status of fisheries separately for each of the five evaluation fields. Results can also suggest where to emphasise future research and the wise use of limited resources. The works of Preikshot *et al.,* (1998), Preikshot and Pauly (1998), Pauly and Chuenpagdee (2003) and Baeta *et al.,* (2005) for tropical and small-scale fisheries are good examples. However, Rapfish is not intended to replace conventional stock assessment procedures used to formulate management tools like quotas (Pitcher, 1999). In this chapter the status of 26 major fisheries from 5 countries in the Red Sea are evaluated using Rapfish.

2.3 Materials and methods

2.3.1 Sources of information

Based on the information available during this research, 26 major fisheries in the Red Sea were identified for Rapfish analysis. Since there was limited information these 26 fisheries cannot be taken, by any means, to be exhaustive. Table (2.1) lists the Red Sea fisheries included in this research, the code given to them for graphical purposes and whether they belong to artisanal or industrial sector. Because of their migratory behaviour and since information available during this research for shark fishery was for the whole Red Sea, the shark fishery is for all the Red Sea countries together. I used five evaluation fields, namely ecological, economic, technological, social and ethical, comprising a total of 44 attributes to evaluate the sustainability of the fisheries. The list of attributes, their definitions, scoring ranges in their respective evaluation fields are given in the Appendix (Table A.1). In order to be able to compare results from different Rapfish analysis of different fisheries, it is recommended to use the same attributes**.**

An exhaustive search of published papers, reports and fishery statistics literature supported the scoring of the attributes. The Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA) provided information for all the countries in the region (Hariri *et al.*, 2000). Saudi Arabian fisheries were scored using official annual fisheries reports (MFD, 1997; MAW, 2008) while Habteselassie and Habte (2000) was useful for Eritrean fisheries.

Table 2.1 Red Sea fisheries analysed using Rapfish, their numbers in the MDS ordination graphs and categories.

Fishery	Number for graphing	Category
Egyptian purse seine	1	Industrial
Egyptian trawling	2	Industrial
Egyptian reef associated fishery	3	Artisanal
Sudan artisanal, fin fish	4	Artisanal
Sudan artisanal, shell fish	5	Artisanal
Sudan industrial	6	Industrial
Yemen Houri	7	Artisanal
Yemen Sambuk	8	Artisanal
Yemen trawlers	9	Industrial
Yemen shrimp	10	Industrial
Eritrea-Houri hook and line	11	Artisanal
Eritrea-Houri gillnet	12	Artisanal
Eritrea-Sambuk Hook and line	13	Artisanal
Eritrea-Sambuk Gillnet	14	Artisanal
Eritrea-diving	15	Industrial
Eritrea-longline	16	Industrial
Eritrea-trawlers	17	Industrial
Eritrea-shrimp	18	Industrial
Saudi Arabia-handline	19	Artisanal
Saudi Arabia-gillnet	20	Artisanal
Saudi Arabia-trolling	21	Artisanal
Saudi Arabia-trap	22	Artisanal
Saudi Arabia-trawlers	23	Industrial
Saudi Arabia-purse seine	24	Industrial
Saudi Arabia-shrimp	25	Industrial
Shark fishery (whole Red Sea)	26	Artisanal

Some information for ecological attributes were collected from FishBase (Froese and Pauly, 2012), and some socio-economic information was obtained from the CIA world fact book (CIA, 2004). Personal contacts with fishery experts from the region and my own observation and experience in the Red Sea provided additional sources. Since information was not available for all the fisheries about the attribute "equity in entry to fishery" of the ethical analysis, the mid score was given to all the fisheries so that it would not have an influence on the distance matrix and the final relative status results.

2.3.2 Rapfish analysis

In order to have fixed reference points with which the fisheries can be compared, Rapfish includes a "good" or "perfect" fishery (defined as 100% sustainability score), consisting of the best possible scores for all the attributes in the respective evaluation fields, and a "bad" or "worst" fishery (defined as 0% sustainability score), which has the worst scores. In addition, two "half-way" scores, which are mirror images of each other to scale the vertical dimension, and a set of pre-defined anchor points in order to avoid vertical "flipping" of the MDS ordinates are included. A more detailed account of the reference and anchor points is given in Kavanagh and Pitcher (2001).

Scores were normalised to Z-values so that all have equal weight in the distance matrix, Euclidean distance squared was used as a measure of distance. The scores, including the reference fisheries, in each evaluation fields were analysed with MDS using the well-known ALSCAL method (Kavanagh and Pitcher, 2004). By convention, the MDS output was rotated so that the "good" to "bad" reference vector is horizontal and scaled between zero and 100%. Since the ALSCAL iteration is an optimisation procedure, ordination errors are indicated by a "stress" value greater than zero: stress values more than 0.25 are considered unreliable (Clarke and Warwick, 1997), but none of the analyses used here exceeded that value. Scoring uncertainty was expressed for each evaluation field using Monte Carlo sampling from a triangular distribution with maximum and minimum values for each score. A 100 simulation runs were made and the median and the 50% inter-quartile range of the scatter were obtained (Alder *et al.*, 2000). The paper (Tesfamichael and Pitcher, 2006) published based on this chapter is the first to apply the uncertainty analysis that has been recommended in previous Rapfish applications (Pitcher and Preikshot, 2001).

In order to determine which attributes have proportionally larger influence on the results, each attribute was sequentially dropped from the MDS analysis for each evaluation field (jack-knifing), providing a value for the percentage influence of each attribute on the overall ordination "leverage" (see Pitcher and Preikshot, 2001). Further analysis was carried out by combining the fishery scores to enable overall comparisons among countries using a kite diagram (Pitcher and Preikshot, 2001). In addition, results were pooled to enable comparison between fisheries on the west and east coasts, and between artisanal and industrial fisheries of the Red Sea.

2.4 Results

The two-dimensional plots show the sustainability status of the fisheries from the MDS ordinations (Figure 2.1). The fisheries are distributed on the X-axis according to their sustainability in the specified evaluation field. The vertical distribution of the fisheries on the Y-axis shows that different combinations of scores can result in similar sustainability values in the ordination. It expresses differences not related to sustainability (Pitcher and Preikshot, 2001). Kruskal's stress formula 1 and squared correlation (RSQ) provide diagnostic and goodness-of-fit statistics for the MDS (Table 2.2).

The ecological and technological ordinates for the fisheries have a wider distribution on the X axis than the other fields (Figure 2.1), while economic results are clumped and the social and ethical ordinations have a main clump with a few outliers. In all the ordinations, except ecological and technological, there is a general trend for most fisheries to lie in the left half of the sustainability axis, lower than 50%. Most ecological ordinates on the other hand are shifted to the right, the average always higher than any other field. This effect has been observed in most previous Rapfish ecological analyses, (e.g., Pitcher and Preikshot, 2001; Baeta *et al.*, 2005) and, before the sources of this upward shift are investigated in more detail, I have adopted the convention of adjusting the overall mean of ecological field results to 50%. The averages for all other fields are generally close to 50%.

In the ecological evaluation field, the top quartile fisheries for sustainability are Sudanese artisanal fin fish (fishery #4) and Eritrean artisanal fisheries (11, 12 and 13); whereas in the social ordination the top quartile is made up of only industrial fisheries (10, 1, 9, 2, 6, 24 and 16). The best fisheries in the economic field are the Eritrean diving fishery (15) and shark fishery (26). Technologically the most sustainable fisheries are the Eritrean diving (15), Saudi Arabian trap (22) and Saudi Arabian gillnet (20) fisheries. In the ethical ordination, most of the fisheries are clumped about mid way and there are many overlaps; industrial fisheries lie to the left, i.e., are evaluated as less sustainable (e.g. 6, 17 and 2).

Table 2.2 Kruskal's stress and RSQ for the different evaluation fields.

Evaluation fields	Kruskal's stress*	RSQ
Ecological	0.20	0.91
Economic	0.17	0.92
Social	0.19	0.88
Technological	0.18	0.87
Ethical	0.20	0.91

* Kruskal's stress value less than 0.25 indicates a good fit.

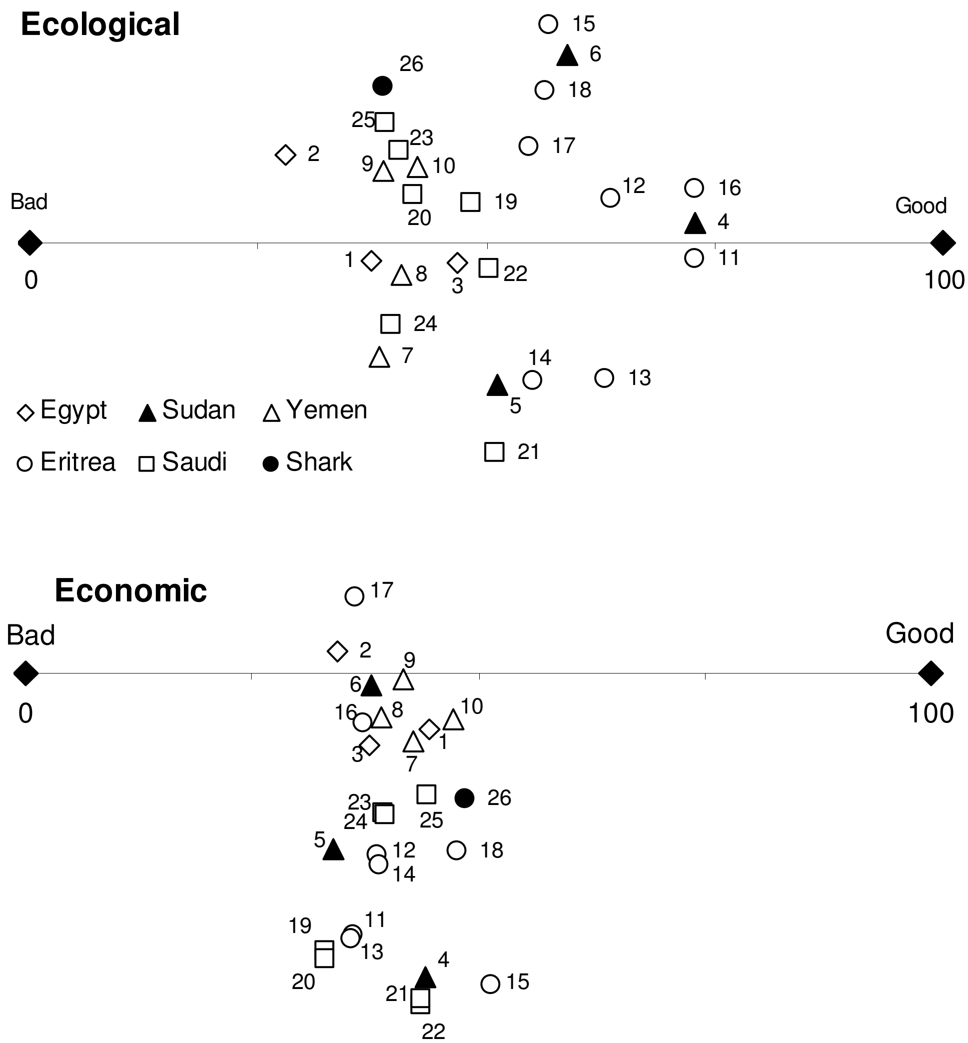
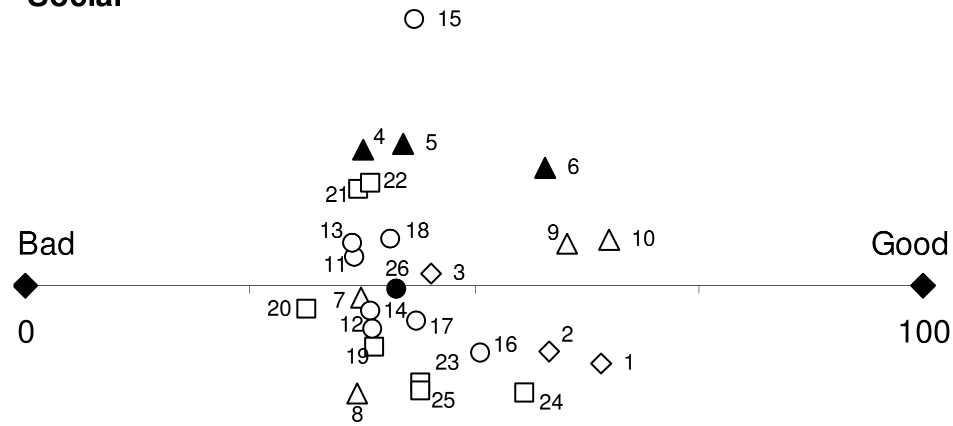
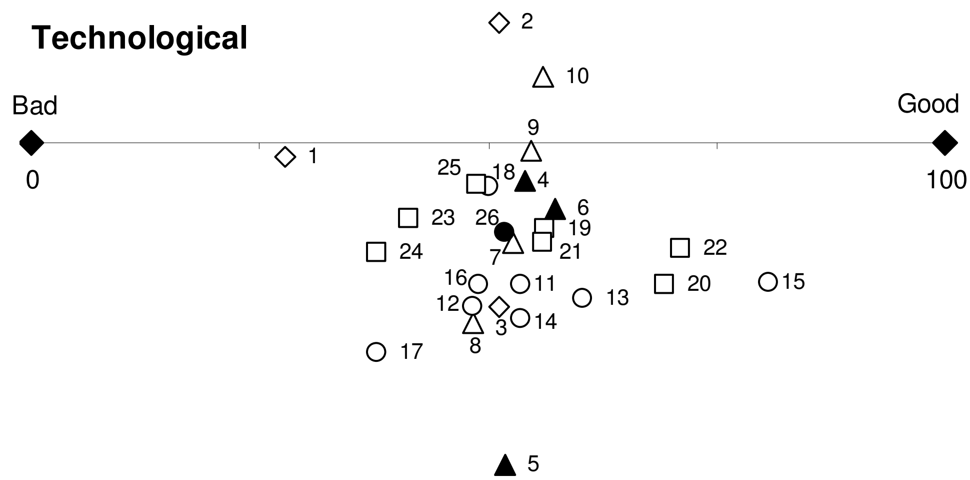


Figure 2.1 Two dimensional Rapfish plots of the MDS ordination of the Red Sea fisheries. The numbers represent the fisheries as given in Table 2.1 (figures continue next pages).

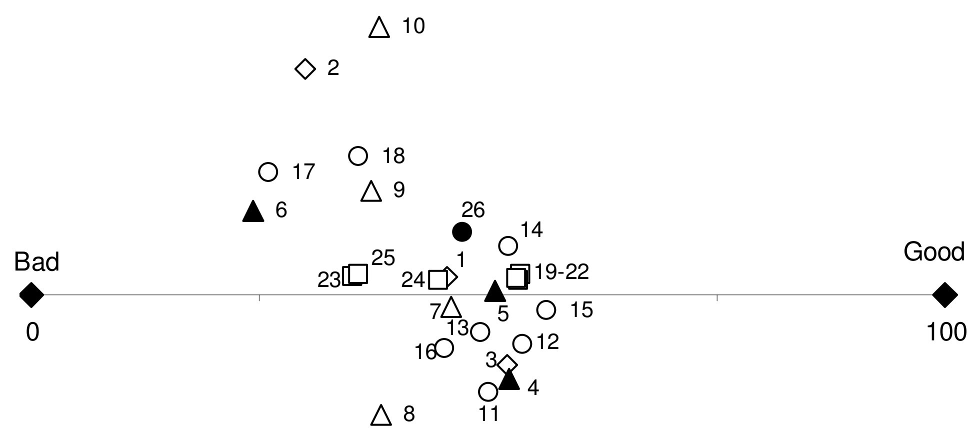
Social



Technological



Ethical



The 50% inter-quartile range (IQ) is chosen to display uncertainty rather than the 95% confidence interval on the median, because the error bars for the latter were very small. The IQ error bars on the median positions for each fishery are quite narrow in all fields. An example is given in Figure (2.2) for the ecological field; IQ error bars for the other fields are not presented as they are similarly narrow. A 100 random runs were found sufficient to stabilize the error variance.

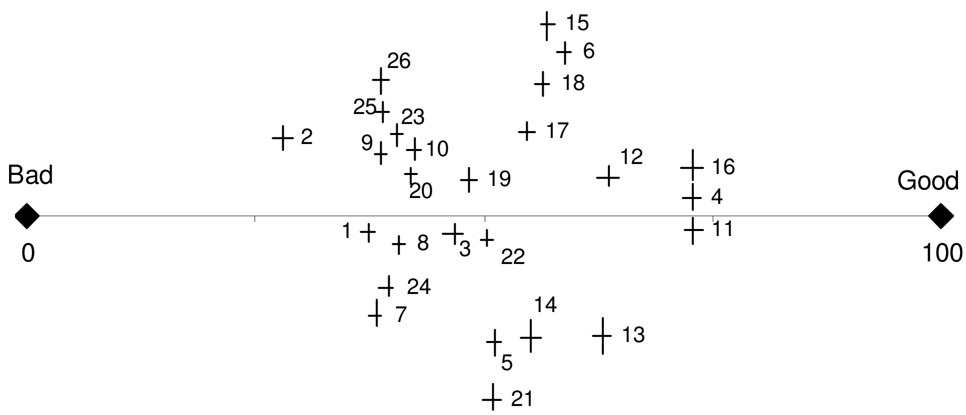


Figure 2.2 The inter-quartile (IQ) ranges, or 50% of the scatter, of the Red Sea fisheries in the ecological field.

The leverage results indicate how much each attribute influences the estimated ordination status of the fisheries (Table 2.3). The values given are the mean standard error of the shift on the X-axis when that specific attribute is dropped. All of the attributes have leverage less than 10% and are relatively similar; this is interpreted as meaning that no single attribute dominates the analysis, all are of roughly equal importance, and there are no candidates to be dropped on statistical grounds. Relatively, the technological field has the widest range of leverage values; "selective gear" and "trip length" are the highest and the lowest, respectively.

Table 2.3 Leverage of attributes, given by mean standard error (SE), in their respective evaluation field.

Ecological		Economic		Social		Technological		Ethical	
Attribute	SE	Attribute	SE	Attribute	SE	Attribute	SE	Attribute	SE
Change in Trophic level	3.41	Marketable right	5.82	Fishing sector	4.93	Selective gear	6.07	Just management	4.56
Recruitment variability	3.39	Ownership/transfer	5.76	Conflict status	4.74	Pre-sale processing	5.43	Mitigation of habitat destruction	3.60
Migratory range	3.38	Other income	5.70	Education level	4.54	On-board handling	4.79	Equity in entry	3.51
Size of fish caught	3.36	Sector employment	4.86	Fisher influence	4.34	Vessel size	4.74	Alternatives	3.35
Catch < maturity	3.32	Subsidy	4.71	Environmental knowledge	4.14	Fish attraction devices (FADS)	4.67	Mitigation of ecosystem depletion	3.28
Species caught	3.13	Market	4.05	Fishing income	3.66	Catching power	4.43	Illegal fishing	2.98
Range Collapse	3.04	GDP/person	3.89	New entrants into the fishery	3.10	Landing sites	2.85	Adjacency & reliance	2.30
Discarded bycatch	2.49	Limited entry	3.68	Kin participation	2.44	Gear side effects	2.63	Discards & wastes	1.52
Exploitation status	1.83	Average wage	3.58	Socialization of fishing	2.20	Trip length	1.84		

All countries have similar values ethically and economically (Figure 2.3), and in the technological field all countries have similar values except Egypt, which has lower sustainability. The main differences are in the ecological and social fields. Eritrea and Sudan have the best scores ecologically. In the social field, Egypt has the best score, then Yemen followed by Sudan, Eritrea and Saudi Arabia. The west and east coast of the Red Sea scored the same in all fields, except ecological where west coast fisheries scored better than the east (Figure 2.4a). The economic sustainability evaluation of industrial and artisanal fisheries is similar, but the artisanal sector does better in ecological, technological, and ethical fields. Surprisingly, the industrial sector rated higher in the social evaluation (Figure 2.4b).

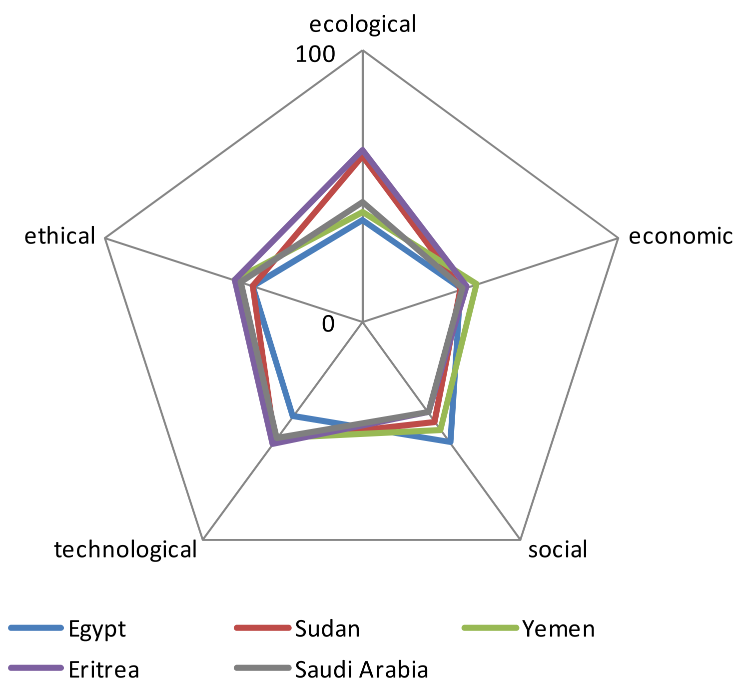


Figure 2.3 Kite representation of the evaluation of Red Sea fisheries grouped by countries.

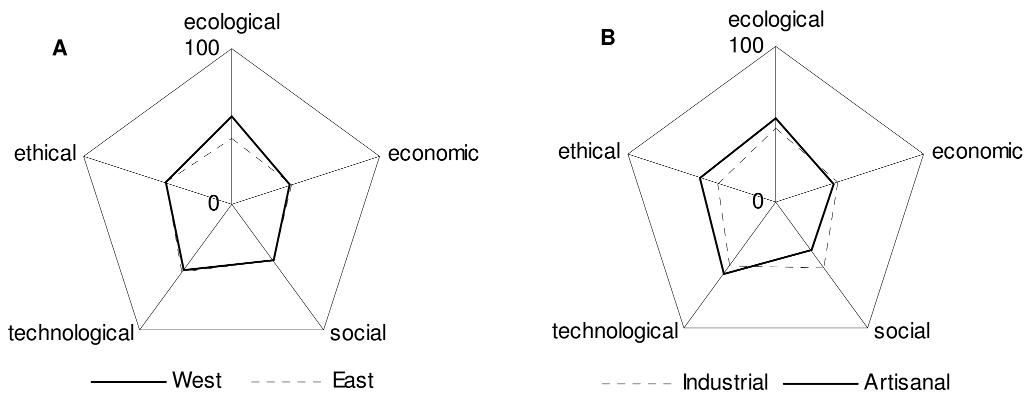


Figure 2.4 Comparison of the different aspects of Red Sea fisheries. A) West and east coast fisheries. B) Industrial and artisanal fisheries.

2.1 Discussion

The Rapfish evaluations suggest that the sustainability of fishing activities is quite similar in all the countries bordering the Red Sea. Generally, the largest difference is observed between artisanal and industrial fisheries (Figure 2.4b). The artisanal fisheries are ranked better than industrial in ecological, ethical and technological evaluation fields, while it is the reverse in the social field and they have similar economic status. The pressure on the ecosystem from artisanal fisheries is not very high because they are mainly for subsistence and their number is not very big as the coast is less populated. Technologically, these Red Sea artisanal fisheries use relatively more selective and passive gears, while the industrial fisheries use active, non-selective gears, which are more destructive to the ecosystem. Industrial fisheries also use more sophisticated technology and have bigger boats with better handling capacity, which adds up to higher pressure on the ecosystem. In the Red Sea, most small-scale fisheries do not have well developed technology at their disposal, especially for handling the catch. Sometimes a considerable amount of the catch perishes due to lack of ice and freezing facilities (Sanders and Morgan, 1989). This hinders them from taking large amounts of fish from the ecosystem. In countries like Sudan, ice is available only in the major fish landing harbours, and most fishers far from these locations are mainly involved in shell collection.

Economically, there is the general perception that industrial fisheries are more efficient and profitable than small-scale artisanal. However, according to the Rapfish analysis, which looks into factors that affect the long term economic sustainability of the fisheries, the artisanal fisheries have very close economic sustainability status to industrial ones (Figure 2.4b). Thus, the argument that artisanal fisheries should be replaced by industrial for economic reasons, which is common in many developing countries such as the Red Sea countries, should be challenged in relation to long term sustainability.

Industrial fisheries ranked better than artisanal in social status, and so did the Egyptian fisheries, which are mainly industrial. This high social evaluation could be a combined influence of attributes such as "fishing sector", "educational level" and "fisher influence" (see Table A.1 in the Appendix for the definitions of the attributes) in the social field where the industrial fisheries scored higher than the artisanal. In addition, as can be seen in Table (2.3), these attributes have a higher leverage (influence) on the ordination than attributes where artisanal fisheries scored better such as "kin participation" and "socialization of fishing". The outcome of this research, however, does not negate the general thinking that artisanal fisheries provide more employment opportunities than industrial. This is reflected in Rapfish in the attribute "sector employment" in the economic field where artisanal fisheries scored better. It is important to note that the interpretation of the results of Rapfish should be performed in relation to the definition of the attributes in the different evaluation fields (Table A.1 in the Appendix).

Another major difference between artisanal and industrial fisheries, which directly affects their overall ethics of resource exploitation, is their geographic proximity and historic connection with the ecosystem. Artisanal fisheries in the Red Sea are local to the coast and the ecosystem has been major part of their livelihood and has traditional and cultural values. However, the industrial fisheries are not usually based in the coastal area, most of them are from foreign countries, and their main interest is in making quick money and moving to another place when it is no longer economically feasible to fish. The artisanal fisheries have longer term attitude than the industrial fisheries and this attitude is a critical element of sustainability, so due attention should be given in decision making and not only to the short term profit making. Status values for the ethical ordination are clumped together except for the industrial fisheries, which are to the left of the artisanal (Figure 2.1), i.e., industrial scored worse than artisanal. The artisanal fisheries of the region are more or less similar in terms of their "fishing habits" and hence in their ethical status. The fact that the same score was given to all the fisheries for the attribute "equity in entry to fishery" in the ethical field may have contributed to the clumping of the results.

The difference between the artisanal and industrial is interesting because there are some conflicts between the two sectors. Based on the analysis, the following management recommendations can be made. It seems better to encourage artisanal fisheries so that the long term sustainability of the resource is better ensured. Because the only field in which the artisanal fisheries ranked less than the industrial is in the social field, helping the artisanal fishers in those attributes, especially education and direct involvement in the management, can be a helpful incentive to the overall sustainability of the ecosystem and the fisheries.

The difference between countries is not as obvious as it is between artisanal and industrial. In fact, the fishing operations of the artisanal fisheries, in terms of boats, facilities, gear, fish storage, are similar in all Red Sea countries. There are differences in other aspects, though. For example per capita fish consumption is the highest in Yemen, followed by Egypt, while the lowest consumption is in Eritrea and Sudan (Sanders and Morgan, 1989). Head (1987c) predicted Sudan and Eritrea would be the countries to benefit the most from expanding the fishing industry in the Red Sea. The fact that Sudan and Eritrea are the countries which utilize their resources least is clearly seen in Figure (2.3); these two countries have the highest ecological sustainability status. This is reflected also in the comparison between the west (Egypt, Sudan and Eritrea) and east (Saudi Arabia and Yemen) Red Sea fisheries (Figure 2.4a). The Red Sea fisheries have been sustainable, with some exceptions such as the Egyptian shrimp fishery in the Gulf of Suez, due to lack of efficiency and proper market structure (Sheppard, 2000).

Malthusian overfishing may be a problem in many small-scale fisheries in developing tropical countries (Pauly, 1994). It is characterised by pressure on fishery resources from rapid population growth, poverty, shortage of food and lack of alternative economic activities combined with open access to the fisheries. However, until now the problem has not been evident in the Red Sea, as the coast is less populated because of its harsh weather. Nevertheless, recent developments may change this situation. Increased technological development (e.g., air-conditioners) associated with relatively cheap energy from oil (at least for the oil-producing countries), are making the coast an easier place to live; a typical example is the development of many towns on the Red Sea coast of Saudi Arabia. Another booming development is tourism. The Red Sea, especially its diverse coral reef ecosystems, attracts many tourists: in many cases this is not well controlled and can have a deleterious effect on the coral reefs.

The error bars for the estimated median in the Monte Carlo simulation are narrow. This indicates that uncertainty in the analysis is low. It is obvious from Table (2.3), that all the attributes do not have equal influence in their respective evaluation fields. The attributes which scored high in leverage should be given due attention in the future planning of sustainable fishery in the Red Sea. For example, the attribute “selective gear” in technological field has high influence on the ordination; this is a cue for management to take steps to improve the selectivity of fishing gears employed. This is true for the other attributes as well.

As the scoring was done by experts’ judgments based on reports from the region and their personal experiences, it did not necessarily need new quantitative data for the attributes, although, of course, the analysis would definitely benefit from that. Indeed, for robust management advice, new quantitative data from the field are very helpful. So, further empirical research to improve the accuracy of the attribute scores is required. Nevertheless, the results of this preliminary research can be used to improve Red Sea fisheries management, and to identify characteristics of the fisheries to measure in the field. This information provides crucial guidelines where financial, human and institutional resources for fisheries are very limited, as in the Red Sea countries.

CHAPTER 3: Analysing changes in fisheries using interviews to generate long time series of catch per effort

3.1 Synopsis

The data requirements for most quantitative fishery assessment models are extensive and most of the fisheries in the world lack time series of the required detailed biological and socio-economic data. Many innovative approaches have been developed to improve statistical data collection for fisheries. Here, I explore the use of data from fishers' interviews to generate time series of catch rates. A total of 472 standardized interviews were conducted with 423 fishers along the southern Red Sea coast in 2007 recording the best catch they recalled having made, and the change in average catch rates compared to when they started fishing. The results showed decline in the catch rates in all fisheries, ranging from 3.6% - 10.3% per year for more than 50 years. The rate of decline of the typical catch was higher for fishers who started fishing in recent years, suggesting that the resource base is declining, which agrees with other indicators. It is suggested that this can be generalized, and that artisanal fisheries research can be designed around data acquired from fishers through interviews, and their subsequent analysis. This method can be used as a quick and less costly approach to generate time series data, which can be used to supplement other data recording systems, or used independently to document the changes that occurred in fisheries over up to a lifetime.

3.2 Introduction

3.2.1 Data needs in fisheries science and management

The data requirements for the empirical assessment of fishery systems, with humans as part and parcel of the system, are extensive, and generally due attention is given to local, regional and international organizations that usually generate such data. Also, sophisticated statistical methods for data sampling and analysis have been developed to bridge the gap between data requirements and availability. Generally, fishery data are divided into fishery independent and fishery dependent, and usually, a combination of both is used for actual assessment. Fishery independent data are usually gathered by research organizations, and obtained from platforms others than fishing crafts, typically research vessels, while the other data type is obtained from the fishery itself, as the name indicates. The most basic and informative data in fisheries science are time series of catch and effort (Caddy and Gulland, 1983; Pauly and Zeller, 2003), from which catch per unit effort (CPUE) can be calculated and, with caution, it can be used to infer abundance (Harley *et al.*, 2001)**.** The caveat is due to the fact that CPUE is, in some cases, not proportional to abundance; rather, it may remain stable ('hyperstability') while abundance is declining, for example when schooling fishes or spawning aggregations of non-schooling fish are exploited (Hilborn and Walters, 1992; Pitcher, 1995; Sadovy and Domeier, 2005)**.** On the other hand, CPUE may decline more than the actual decline of abundance, a phenomenon called 'hyperdepletion' (Hilborn and Walters, 1992). This can happen, for example, when only a portion of the population is vulnerable to the fishery (Walters and Bonfil, 1999; Kleiber and Maunder, 2008). In most cases, however, CPUE can be a good indicator of resource abundance, again when used with caution.

The most common practices in fishery dependent data collection have been log books filled by the fishers themselves, data collection by technicians at fish landing sites, data collected by onboard observers, and recently, technology-intensive vessel monitoring system (VMS). One common denominator for both the fishery-dependent and fishery-independent data gathering methods is that they both provide a metric of the fishery or the resources at the moment the sampling is done, i.e., they can only generate contemporary data.

Most data collection by fishery management organizations emphasize industrial fisheries (McCluskey and Lewison, 2008). Small scale fisheries, which account for more than 95% of the world's fishers and are critical to the socio-economic life of the communities in which they are embedded (Berkes *et al.*, 2001; Pauly, 2006; Andrew *et al.*, 2007) do not, however, get due attention. It is also estimated that about a third of the global catch (Chuenpagdee and Pauly, 2008) and half of the sea food directly consumed by humans originate from small scale fisheries (Pauly, 2006). In the Red Sea, the small scale fisheries contributed up to 70% of the total retained catch since 1950 (see Figure 4.3 in Chapter 4). Thus, a form of fisheries research which takes the small-scale fisheries into full consideration appears imperative (Berkes *et al.*, 2001).

3.2.2 Tapping into fishers' memory or knowledge

Even if information about the small-scale (or 'artisanal') fisheries is not available in official records, it does not mean there is no information at all. Considering only official records, as has been the common practice in traditional stock assessments, and not using the information that the fishers themselves hold is limiting ourselves (Johannes *et al.*, 2000). Indeed, re-acquiring information from the memory of resource users is gaining more attention in fisheries research (Johannes *et al.*, 2000; Sáenz–Arroyo *et al.*, 2005; Haggan *et al.*, 2007). In the process, several methods have been developed to incorporate fishers experience, knowledge and information into fisheries assessment. These approaches depend on the recollection of people who have been involved in fishing, i.e., fishers who have lived in close proximity to the fishery resources, such that they could witness the changes that occurred, and use interviews to capture historic trends evolution from individuals' memories. These approaches can be an important source of information and sometimes the only one, for example in societies with strong oral traditions.

Most of interview-based research with natural resource users so far has been of an anthropological nature, or with an emphasis on the socio-economic dynamics of the communities, with little or no attention devoted to the status of the resources exploited in the community in question (Pauly, 2006; Anadón *et al.*, 2009). In addition, anthropological research is usually qualitative, and aims to understand the perceptions, values, opinions and institutions of resource users (Salmi, 1998). These are important and an integral part of resource management, because following even the best stock assessment, policies must be implemented which affect people, i.e., which have implications for resource users and their livelihoods. However, qualitative anthropological research (i.e., much of the tropical fisheries research performed by maritime anthropologists) remains incomplete because it fails to use a metric for the main activity of the people it studies, who we might recall, spend most of their waking time fishing, or improving their tools and methods to catch fish (Pauly, 2006).

Interview-based methods to acquire quantitative information have been used to comprehend past systems, e.g., to describe historic change in the abundance of a target species or change in species composition of the catch of depleted fishing grounds (Sáenz-Arroyo *et al.*, 2005; Sáenz–Arroyo *et al.*, 2005; Bunce *et al.*, 2008; Lozano-Montes *et al.*, 2008). Fuzzy logic has been applied, in some cases, to standardize and quantify qualitative data collected through interviews (Mackinson, 2001; Ainsworth *et al.*, 2008). However, interview-based approaches have been used not only to acquire past data, but also for contemporary analyses as well, for example preliminary assessment of the ecological and socio-economic sustainability of fisheries (Teh *et al.*, 2005), or to obtain information on the by-catch that is omitted in landing recording systems (Moore *et al.*, 2010). Also, since different fisher age groups can be interviewed, interview-based methods have been very useful in quantifying cases of the shifting baseline syndrome (Pauly, 1995; Sáenz-Arroyo *et al.*, 2005).

3.2.3 Methodological, standardization and accuracy issues

Interview-based methods depend on the cognitive faculty of interviewees and have been used for collecting data in wide space and time relatively at low cost (Neis *et al.*, 1999; Anadón *et al.*, 2009; Moore *et al.*, 2010). However, interview protocols that are not standardized hinder comparison as estimates derived from interviews can be sensitive to the methodology used (Fowler Jr, 2009; Moore *et al.*, 2010). The main liability of interview-based data collection has been its questionable reliability. There are not many studies that investigated this issue directly, because most fisheries researchers have used interviews mainly to fill in data gaps (Baelde, 2003). There are studies, however, which used interview simultaneously with other methods to assess fisheries. Some of the researches, when studying the same fisheries, found similar trends and reached similar or complementary conclusions (e.g., Neis *et al.*, 1999; Otero *et al.*, 2005; Begossi, 2008; Lozano-Montes *et al.*, 2008), while some generated mixed results, i.e., there were similarities in some indices and not in others (Daw, 2008; Silvano and Valbo-jørgensen, 2008).

There are two main kinds of biases, which may affect the accuracy of responses (Daw 2010): retrospective bias and a tendency to distort facts because of their perceived potential to affect management or policy (Bradburn *et al.*, 1987; Henry *et al.*, 1994; O'Donnell *et al.*, 2010). The research on the accuracy of people's memory has been mainly in psychology, where the use of retrospective methods to reconstruct past events has been widely debated (Henry *et al.*, 1994); however, empirical research on the related bias is rare even in psychology (Koriat and Goldsmith, 2000). In a paper evaluating retrospective methods for comparing past data collected through interview (retrospective) and data measured independently in the past, such as archival material (prospective), Henry *et al.*, (1994) reported that cognitive and motivational factors may lead to inefficient and inaccurate processing of past information. They also found that for variables measured along dimensional scale (quantitatively measurable variables), there was a strong correlation between the retrospective and prospective data, while the correlation was poor for psychosocial variables (subjective psychological states). And even for strongly correlated quantitative variables, accuracy was poor, mainly because of a systematic tendency by the interviewees to shift their estimates toward desirable states. However, this bias was not a memory recall error as contemporaneous reports also showed similar bias. Similarly, interviews used in fisheries research can be used to track relative changes (e.g., patterns), while the utmost caution is required when absolute values are in play. Thus, the values gathered through interviews should be checked against independently measured parameters, which can be used as an anchor to translate the interview data to an absolute scale, as is done, for example, when estimating unreported fisheries catches from anecdotes (Pitcher *et al.*, 2002; Tesfamichael and Pitcher, 2007).

There are few studies in fisheries that assessed quantitatively the accuracy of fishers' interview data. O'Donnell *et al.*, (2010) examined the possible effects of interview accuracy in conservation assessment by running two scenarios: one where the interview data was assumed to be accurate and the other where the fishers were assumed to overestimate or exaggerate their responses. They found out that accuracy can be a serious problem in the assessment of the resource and suggested that the accuracy assumption built into the interview data must be explicitly stated. Otero *et al.*, (2005) compared catch rate and total catch from interviews with official reports. They found that the two sources correlate positively, but that the total catch from interview was higher than the official one, which, they suggested, was due to unreported catch not being included in the official statistics. In this case, interview gave more accurate results than official statistics. Daw *et al.*, (2011) compared CPUE data from interviews, official report and underwater visual census and found disagreement among them. They concluded that each data source had its own limitations and bias, and that none can be taken as the 'true' value. Even the most independent abundance measurement, underwater visual census, had sampling problems (e.g., depth limitation) and there was also a mismatch between the area sampled by the visual census area and the fishing grounds (Daw, 2008; Daw *et al.*, 2011). O'Donnell *et al.*, (in press) compared CPUE data from interview, logbook and official catch landing records. While they found that all sources showed similar trends, absolute CPUE values from interviews were higher and more variable, and there was no correlation between interview reports and official landing records. Again the higher CPUE could be due to the inclusion of unreported catch in the interview reports similar to Otero *et al.*, (2005), or exaggeration of their catch by the interviewed fishers.

In this chapter, I describe a protocol to collect time series catch and effort data through interviews and discuss the results and lessons learned. The design of the questionnaire in relation to the objectives of the research, the interview procedure within the context of the research and the culture of the society being interviewed, and an analysis of the data acquired and the results are presented. For comparison purposes, the same protocol was used in three countries and 6 fisheries which were identified by the type of gear. The analysis was used to: (1) quantify the change in catch rate by interviewing fishers recruited to fishing at different times and using the best catch they recalled having made; (2) quantify changes in the typical (average) catch rates of fishers between the time they started fishing and 2007, when the interviews were held. Additionally, present theoretical considerations, from different fields, and empirical examples of the use of interview in fishery research data collection is presented; and the lessons learned for further refinement of interview based procedures to collect quantitative time series catch and effort data is documented.

3.3 Materials and methods

3.3.1 Questionnaire

A semi-structured questionnaire, with some questions open-ended and some not, was used in the interviews, which were carried out in 2007. A semi-structured interviewing method was chosen because it both provides a general framework and also flexibility for the interviewer to probe new ideas as the interview progresses. It also gives a more natural flow of discussion between the interviewer and interviewee (Wengraf, 2001). The questionnaire was subjected to ethical review by the Behavioural Research Ethics Board of the University of British Columbia and restructured according to the reviews. Field testing of the first version of the questionnaire showed that it was too long. The shortened version, as used for the research, is given in the Appendix (B). It had three parts: general bio-data which were asked of all interviewees; specific questions, based on the kind of fishing activity that was involved (usually defined by the kind of fishing gear operated); and finally catch data. As some fishers operated different gears, when they were willing and time allowed, they were asked about these different gears, thus increasing the coverage of gear types.

3.3.2 Sampled areas

The research was carried out in fishing communities in three countries in the southern Red Sea: Eritrea, Sudan, and Yemen (Figure 3.1). Interviews were not done in Egypt and Saudi Arabia, because the Egyptian authorities did not allow field research, and an entry visa could not be secured for Saudi Arabia. In Eritrea, a wide range of fishing villages, from the main port city of Massawa in the north to the Djibouti border in the south, and the villages in Dhalak Kebir Island, were covered. This wide range was possible because of extra support for assistance and transportation funding was available. In Sudan, the main port city, Port Sudan, Mohamed Qol and Dungunab in the north, and Suakin in the south were sampled. In Yemen, only the Red Sea coast was sampled; most of the interviews were conducted in the main fishing port of Hodeidah with a few in Al Koka, in the south (Figure 3.1).

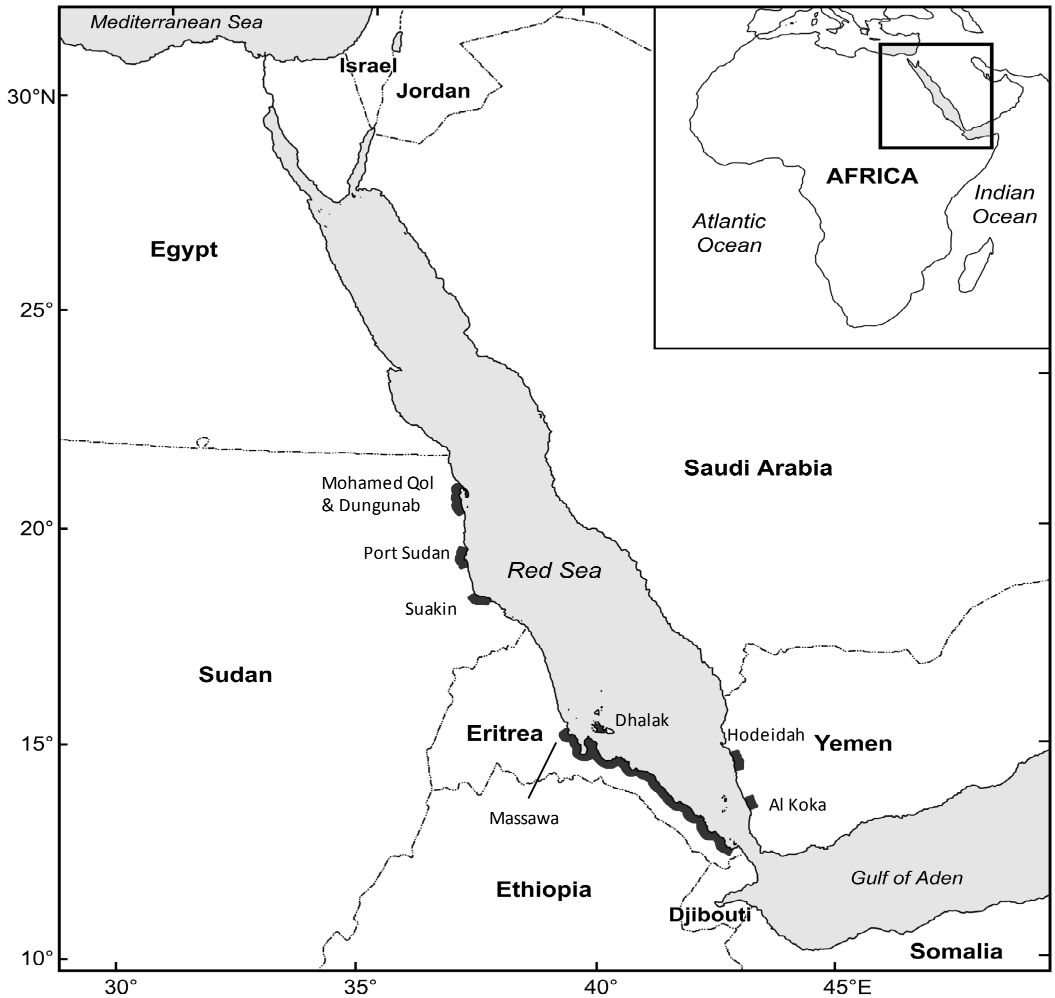


Figure 3.1 Map of the Red Sea indicating the areas (in Sudan, Eritrea and Yemen) where interviews were conducted.

3.3.3 Sampling

In the three countries sampled, an official permit was secured from the authority responsible for the management of the marine sources. A combination of random, snowball and targeted sampling methods were then applied. Assistants who spoke the local languages were trained in the interviewing procedure. Potential interviewees were approached usually at fish landing sites or in their villages. A brief account of the research and what was expected of them was explained to them, and their consent to be interviewed was obtained before any interview was carried out. Effort was made not to interfere with their operations. For example, no interviews were requested when they were operating fishing gear or landing their catch, the latter is critical given that fish quickly starts to spoil in the hot sun of the Red Sea coast. The best time was when they were done with most of their activities and were relaxing, mending their nets or during their days off in their villages. When visits were made to the fishing villages, the elders were first approached and once they gave their blessings for the work to continue, fishers were then interviewed. The elders were very helpful in securing the collaboration of fishers for the interviews. Each interview took on average 30 – 45 minutes, except in the first few pilot interviews, which took longer. The guidelines and recommendations of the Behavioural Research Ethics Board of the University of British Columbia were followed during the interview. In order to protect the privacy of the interviewees, each was given a unique code and no names were written on the questionnaire. In addition, methodological recommendations from Bunce *et al.*, (2002) and Huntington (2000) were considered.

A sample unit in this research is not the individual fisher, but a combination of interviewee and gear type. For example, there were few fishers who were interviewed for two gears; those were taken as two separate samples. Though fishers were interviewed randomly, emphasis was given to the fisheries that have a high contribution to the total catch, rather than spreading the sampling effort thinly over a wide range of fisheries. The gears selected were gillnet, hook and line, and shark for Eritrea; hook and line for Sudan; and gillnet and hook and line for Yemen.

Effort was made to have a wide age range of fishers in the sampling. The samples were reviewed throughout the process to check age distribution. It was not easy to find older interviewees, so targeted requests were made for them. Women could not be interviewed, due to cultural sensitivities, even though they were involved in fishing, usually on foot in shallow waters, and supplied much of the fish consumed in their families (as in the South Pacific; Chapman, 1987). In addition to fishers, community elders and managers were also interviewed for general understanding and historic development of fisheries in their respective areas. The data from the interviews were entered in to a Microsoft Access database with interviewee-gear type combination as unique record identifier.

3.3.4 Standardizing data

Fishers often did not report their catches and efforts in units that could be analyzed and compared directly. For example, catches were given in number of boxes, kilograms, number of fishes etc…. The following standardizations were carried out on the raw data:

- In Eritrea sometimes fish landings were reported in number of sacks, especially in the past; one sack contains 45 kg of fish;
- In Yemen, boxes, locally called *'banker'*, are used especially for Indian mackerel, and are equivalent to 40 kg. Bundles of fishes tied in a rope, called '*mihkal'* are also common in Yemen. It was estimated a bundle holds 5 – 10 kg of fish, and the mid- value of 7.5 kg was used for conversions;
- Sometimes, fishers described their catches by the number of fish caught. In such cases, they were asked to identify the species and their average length. Then the data were converted to weight using length - weight relationships in FishBase (Froese and Pauly, 2012).

Almost none of the shark catch data were provided in total wet (or 'live') weight (TWW), but as dried fin weight, dried meat or wet dressed carcass (gutted, headed, and all fins removed). Also, irrespective of the nature of the product, either fin or meat, most shark data were given in '*farasila*', a common measurement unit for trade in the Indian Ocean for many centuries, and which is equivalent to 16 kg (Campell, 1993). First, all products were converted from *farasila* to kilogram. Dried fin weight (DFW), in kg, was converted to wet fin weight (WFW) using a regression equation fitted to data from Fong (1999).

$$WFW = (1.56 * DFW) + 0.0094, \quad R^2 = 0.99 \qquad \ldots 1)$$

WFW accounts for about 5% of the dressed carcass weight (NMFS, 1993). This commonly used ratio has been challenged as not being sufficiently species-specific (Ariz, 2006; Cortes and

Neer, 2006; Biery and Pauly, 2012). The research aims to examine the Red Sea shark fishery in general and there was not enough data to analyze species separately, so the mean ratio is used. Once the fin and dressed weight are accounted for, what remains is the head and viscera, which account for 18% of TWW (Meliane, 2003). Substituting the ratios, TWW from dried fin, all in kg, is given as:

$$TWW = (16.39 * DFW) - 0.15 \qquad \ldots 2)$$

The other common product of shark fishery reported by fishers is dried shark meat. Based on controlled drying processes, moisture content was found to be 40% of total wet weight when shark meat was dried to a 'safe moisture content' (Sankat and Mujaffar, 2004). The dried shark meat, which is dressed (DDW), was converted to TWW using:

$$TWW = 2.13 * DDW \qquad \ldots 3)$$

3.3.5 Validation of interview data

The validity of the data obtained from the interviewees was verified at different phases of the research. It started during the interview where the answers of the interviewees were queried for extreme and unrealistic answers, e.g., a catch too large to be accommodated by a boat. Interviewers were also able to verify the time references the interviewees used. In most of the interviewed communities, people do not know their ages with any precision, as birth certificates do not exist and the culture is predominantly oral. Thus, all references to calendar time made by the interviewees, e.g., the year they had their best catch, were double checked with major events in the history of the communities, which are anchored in most people's memories (Means and Loftus, 1991). Once the closest historic moment was established, then they were asked how many years before or after that event.

For the amount of catch, they were first asked to express it in kilograms, which they were able to do for the recent times because it is the unit used at landing sites**.** For earlier events, other common measurements such as number of sacks or boxes were used. When their catch amount in kg seemed doubtful, they were asked to express it in the other measurements.

A question with a clear empirical answer was built into the questionnaire to check the validity of responses. The question was 'size of largest fish ever caught', and then the answer was compared with the maximum size reported in FishBase (Froese and Pauly, 2012). The interviewers were able to evaluate the overall reliability of the information they had provided at the end of each interview.

Final validation was done after the data were standardized and entered in to the database, using box plot to identify outliers. Any data point which is less than the first quartile minus 1.5 times the interquartile range or greater than the third quartile plus 1.5 times the interquartile range was considered an outlier hence dropped from analysis, i.e.,

$$X < Q1 - 1.5(Q3 - Q1) or\ Q3 + 1.5(Q3 - Q1) < X \quad \ldots 4)$$

3.3.6 Data fitting

An exponential function was fitted to the best CPUE fishers recalled ever having experienced. An exponential function was selected because the resulting slopes (instantaneous rates of change) can be compared among different fisheries irrespective of the actual (scale) value of the catch. In addition, exponential function, unlike linear, does not cross the x-axis, which is realistic. There cannot be negative CPUE. This follows the principles outlined by Silvert (1981) for selecting a mathematical model, which should be useful, but also in agreement with conceptual framework, behaving reasonably over the entire range of data, and also be compatible with a scientific explanation, i.e., not be selected only because it provides a good fit to raw data. The equation which fulfills these criteria is:

$$f\ (x) = c * e^{r*x} \quad \ldots 5)$$

where: *x* is year, *c* is a constant and *r* is the instantaneous rate at which CPUE changed over time.

Besides the best catch they experienced, fishers were also asked to compare their average, or typical, catch rates between the year they started fishing and 2007, when the interviews were held. This was used to examine changes in the ratio of catch rates since the fishers were recruited into fishing. Regression analysis was carried out between the ratios and the year the fishers started fishing. Since not all fishers started in the same year, the ratio of their average catch rate between the year they started and 2007 is affected by the number of years they have been fishing, which prevents direct comparisons. Hence, the comparisons were enabled by annualizing the ratios, i.e., re-expressing the ratios after normalizing for years fishing. Two types of regression analyses were carried out on the data, one where the whole time series data were considered as a set and another where the data were divided into two sets (segments).

3.4 Results

In total, 472 samples (interview units) were collected from 423 different fishers, ranging from 12 – 83 years in age and with fishing experience of 1 – 65 years. Except for a few cases, most fishers approached agreed to be interviewed, albeit only after the objectives of the interviews were explained to them, and their questions were answered. Four interviews had to be canceled because the interviewees left in the middle of the interview to attend to some urgent business. Effort was made to obtain a relatively good representation of all age groups; however, the oldest age group (>61) was difficult to sample, especially in Eritrea and Yemen. In Yemen, the youngest age group (<30) was better represented in the sample than the other age groups (Figure 3.2). The intermediate age groups (31 – 45 and 46 – 60) were well represented in all three countries.

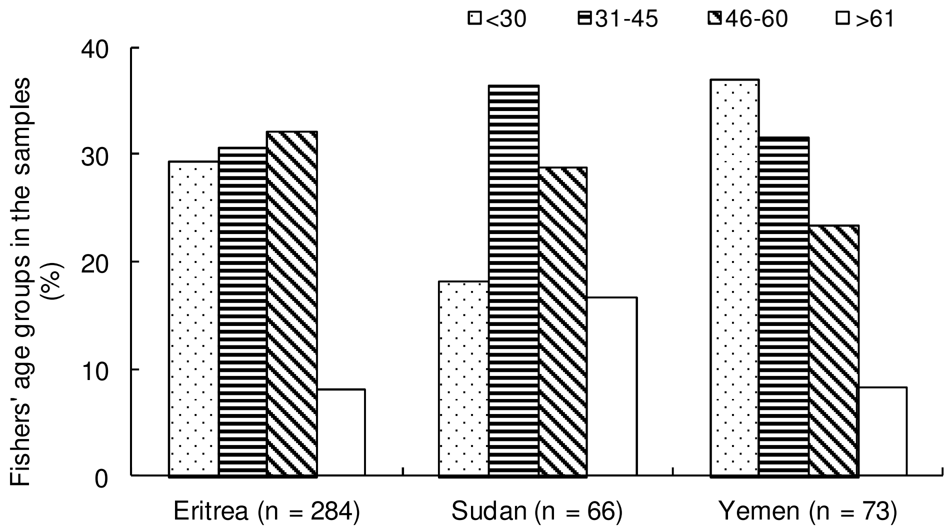


Figure 3.2 Age frequency distribution of interviewees by country.

The analysis of the best CPUE fishers recalled was carried out by gear type because gear characterizes the fisheries very well. There is more similarity in terms of the operation within a fishery of the same gear type (Tesfamichael, 2001). They all showed decline in CPUE (Figure 3.3) in the range of 3.6% - 10.3% per year, the lowest rate of change applying to the Sudanese fishery, and the highest to the Eritrean shark fishery. The other fisheries in terms of CPUE decline were Yemeni gillnet (4.3%), Eritrean hook and line (6.6%), Eritrean gillnet (7.1%) and Yemeni hook and line (8.8%). In addition, comparisons were made among countries, but did not show any clear pattern. Between Eritrea and Yemen, the change in CPUE appeared related to the type of fishery, rather than by geography.

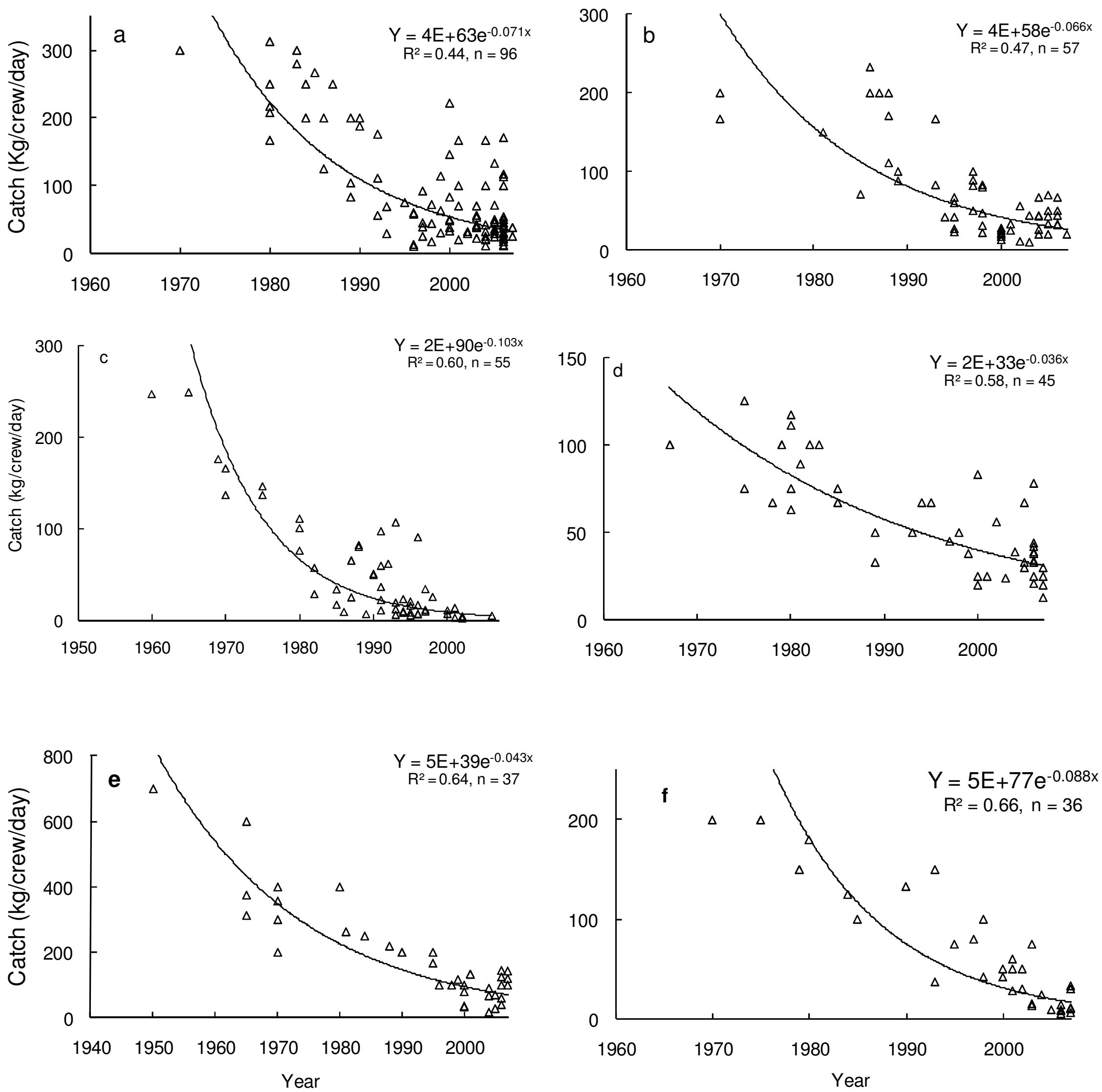


Figure 3.3 Change in best CPUE fishers recalled for: a = Eritrean gillnet; b = Eritrean hook and line; c = Eritrean shark; d = Sudanese hook and line; e = Yemeni gillnet; f = Yemeni hook and line. Note that axes have different scales.

The ratio of typical (average) CPUE from the time the fisher entered to that of the year 2007, when the interviews were held, exhibited wide ranges, i.e., 1.17 – 8 for Eritrea and 1.6 – 25 for Yemen (Figure 3.4). The x-axis is the year the fishers started fishing, which is the independent variable affecting the CPUE change ratio. The declining functions in Figure (3.4) indicate that fishers who started fishing earlier have seen the average catch rate decline more than the fishers who joined recently. The decline in CPUE over time is inescapable in any exploited fishery

(Beverton and Holt, 1957; Hilborn and Walters, 1992). What is interesting is that it was possible to use interviews to quantify the rate at which the decline is occurring. The data in Figure (3.4) do not incorporate the number of years the fishers have been fishing, so when the ratios are divided by the number of years the fishers have been fishing; it yields the annual rate at which the typical CPUE is changing.

When the rates at which the CPUE's change were plotted on a scatter plot, they formed a bi-phasic patterns (Figure 3.5). Two types of regression were used to fit a trend to the points. In the first, one trend line was fitted, assuming there was only one general trend. For the second regression type, the data points were divided into two sets (segments), assumed to represent two distinct patterns. To compare the two types of fitting and test if there is any statistical significant difference between them, an F test was carried out on the sum of squares of the residuals (SSR). The result showed that there is significant difference (Table 3.1); hence, the segmented fittings were used (Figure 3.5), which shows that the decline in CPUE is accelerating in recent years. The breakpoints were determined by the least sum of square of residuals, which were at 1995 and 1997 for Eritrea and Yemen, respectively. To check if the breakpoints were statistically significant than if they were in the neighbouring years, an F test was carried out. In both cases, Eritrea and Yemen (Figure 3.5), the tests showed that they were not significant. Nevertheless, the years with the least SSR were chosen. For Eritrea the least SSR was 0.38 for 1995 followed by 0.44 for 1997; while for Yemen it was 1.64 for 1997, followed by 1.75 for 1994. In both figures, the early portion of the data sets resulted in slopes which are not significantly different from zero, so horizontal lines, which are the averages are used. But in the second segments, there are clear increases in the trends.

Table 3.1 Results of the statistical test comparing the fitting of CPUE change rate data when they were treated as one segment or divided into segments.

	Eritrea (Figure 3.5a)		Yemen (Figure 3.5b)	
Statistic	One segment	Two segments	One segment	Two segments
SSQ	1.83	0.38	2.8	1.64
F calculated	71.79	-	13.16	-
p	<0.05 (3,57)	-	< 0.05 (3,56)	-

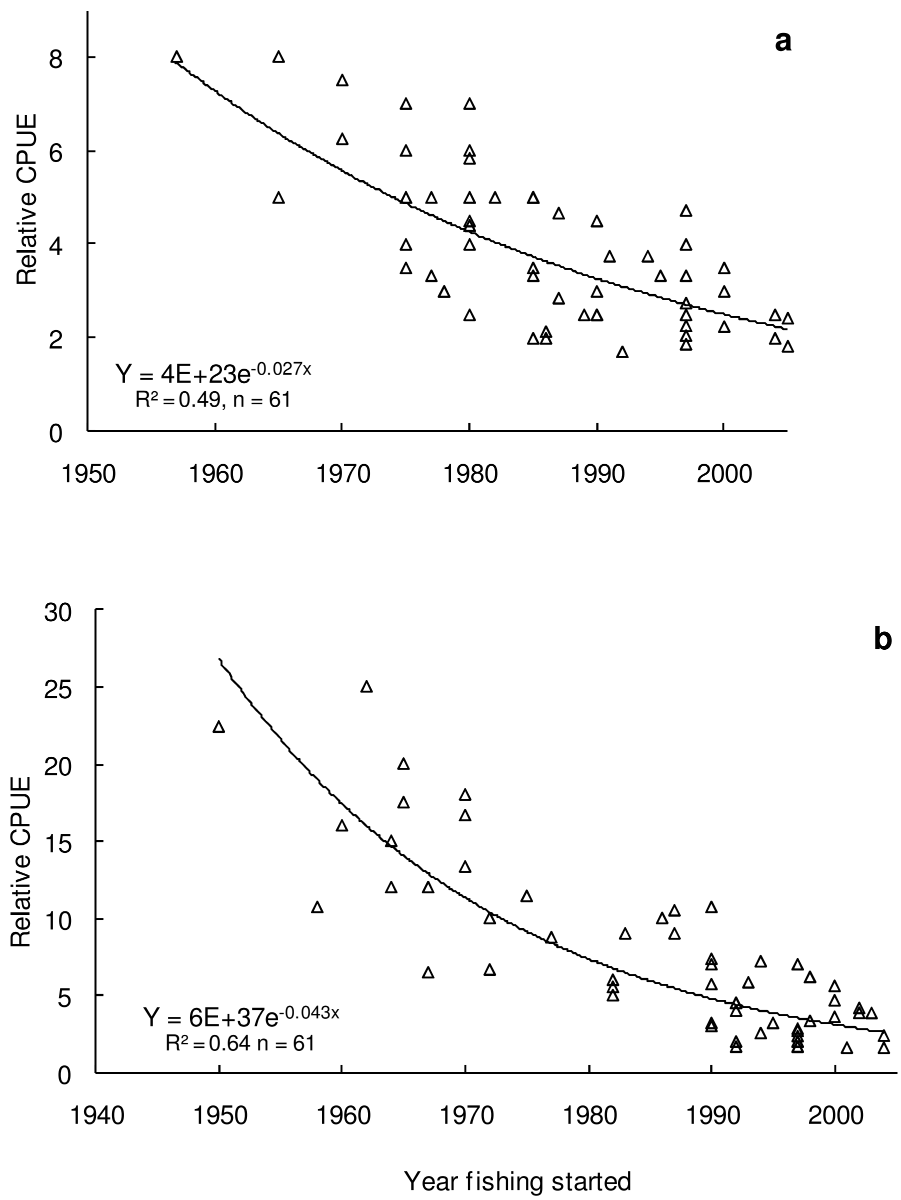


Figure 3.4 Ratio at which the average CPUE changed for interviewees from the year they started fishing, relative to the 2007 CPUE: a = Eritrea, b = Yemen.

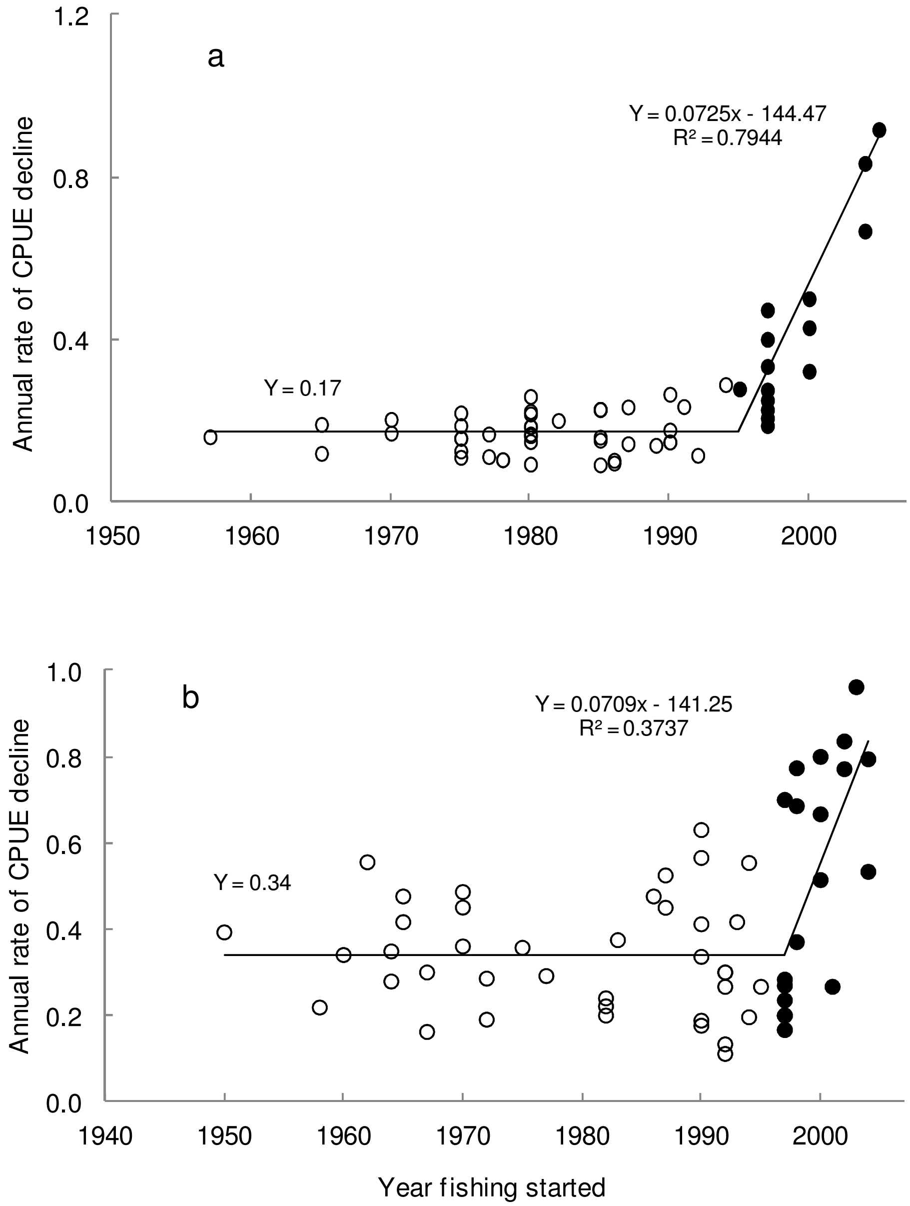


Figure 3.5 Annual decline of CPUE over the years of fishing experience of fishers in two Red Sea countries. (a) Eritrea, where the rate of decline increased in 1995 after the independence in 1991; (b) Yemen, with an increase in the rate of decline in 1997, which is after the unification of the country in 1990 and the start of its oil economy.

3.1 Discussion

In this study I have demonstrated how interview methods can be used to access knowledge lodged in fishers' memory and how various analyses of this information can lead to the recovery of quantitative data. Although the use of fishers' knowledge is getting more attention in fisheries research, how it can be used is still debated. One area where a lot of researchers agree is that a systematic approach during the interview is crucial. What I found in this research is, asking about exceptional experiences of fishers (e.g., the best catch they ever made) and comparing different experiences (e.g., typical catch at different times) allowed fishers to answer the questions more easily than by posing more general or vague questions (e.g., how much is your catch rate changing?). This confirms similar fisheries studies (e.g., Sáenz-Arroyo *et al.*, 2005; Daw, 2008), which found that it is easier to recall events that are unusual or rare.

Besides empirical fisheries studies, there is more evidence of this phenomenon from cognitive psychology as well, which confirms that while it is difficult to recall if memory has many events, unique events can straightforwardly be recalled (Bradburn *et al.*, 1987). These vivid memories of interviewees are referred as 'flashbulb' memories and are characterized by having high personal importance (Rubin and Kozin, 1984). Fishers describe their best catch ever with pride and vividly, similar to the best trophy kill of hunters.

Eliciting memories of best catch requires work. During pilot interviews, fishers were asked a direct question "what is your best catch ever" and almost all the time their answer was "the catch varies as the sea gives". Later, a different approach was used where the question was not directly put forward, rather it was woven into a story "when you go to the sea to fish you do not always catch the same amount, when you are lucky you catch a lot and other days you may even come back empty and lose money. But if you look back, there must be one day where you caught a lot of fish and came back happy". When the question is put in this way, I observed, almost all the time, a light going on in the interviewees face. They smile and start telling their stories with details and do not want to be interrupted. They tell how they went at certain time of the day from a specific dock, the state of the sea, the hotness or coldness of the air, the phase of the moon, the names of all the crew members, how long it took them to pull the net or that they required help from other boats, how tired they were pulling their lines etc… At the end of their stories, they were able to tell the amount of the catch. Thus, I confirm that giving appropriate hints helps as a cue to recall memories, with cue about location and social occasions (e.g., you came back quickly, and all the crew were happy and singing) increasing recall accuracy (Bradburn *et al.*, 1987).

The resulting time series trends and the quantitative comparison between different fisheries they enabled are informative and useful in fishery assessment and management. For example, knowing the rates at which the different fisheries are declining can be used in prioritizing the attention of the fisheries management system, or they can be used as bench marks to evaluate the effectiveness of management schemes. One major challenge, however, is the use of absolute values rather than relative changes. I do not claim the results to be precise estimates of the actual fisheries change over time. However, these values are as informative as other fishery sampling schemes. In some cases they may be even more accurate because they incorporate the unreported catch which is missed by some data recording systems (Otero *et al.*, 2005; Anadón *et al.*, 2009). Besides, many quantitative (non-interview) methods in fisheries are used only to infer relative changes (except for those methods used to set quotas, which this research is not aiming at). In terms of patterns, they are similar to those observed for the Red Sea fisheries using ecosystem modelling (Chapter 6) and rapid appraisal method (Tesfamichael and Pitcher, 2006).

Showing a declining function to fit the best catch rates fishers remembered is not a striking finding, as a declining trend is expected for any strongly exploited fishery resource (Beverton and Holt, 1957; Hilborn and Walters, 1992). However, it was gratifying that it could be quantified so straightforwardly from interviews. This helps to objectively evaluate the states of the fishery over a long period of time (more than 50 years in this case). Also, the rates can be compared to each other. Out of the 6 fisheries analyzed here, the Eritrean shark fishery exhibited the highest decline rate, 10.3% per year. There has been a long history of shark fishing in the Red Sea (Ben-Yami, 1964). The high global demand for shark fin and the life history of sharks combined is having a toll on the shark population. The least decline of Sudanese fishery (3.6%

per year) is not surprising, as the pressure on marine fishes in Sudan is relatively low, because more than 90% of the fish in the country is supplied by fresh water fishery (FA, 2007).

The rapid decline of the annual CPUE for Eritrea in Figure (3.5a) after 1995 fits with the political changes in the region. Eritrea has been in a war for independence until 1991 and the fishery was stagnating for a long time, being conducted only for the daily subsistence of the local coastal population. However, after Eritrea became independent in 1991, programs were introduced to revive the fishery, with investment in infrastructure and financial facilities. After the preparatory phase, the fishery took off and the CPUE decline rate increased starting in 1995 (the breakpoint in Figure 3.5a). This was similar for Yemen (Figure 3.5b); although the change is not as clear as in Eritrea, the decline rate increased after 1997. This matches with the relative stability of Yemen after the civil war, which ended in 1970s, with the unification of the North Yemen and South Yemen in 1990. At the same time, oil revenues started to increase general investments in the country. These two cases are good examples of the significant impacts human actions can have on the ecosystem when the situation allows it, stability in this case. The samples for this analysis were only from Sudan, Eritrea and Yemen. However, some of the results were used for the general Red Sea, i.e., the results were extrapolated to Egypt and Saudi Arabia as well, where sampling was not possible. The artisanal fisheries of the region have very similar culture and their fishing traditions are similar too. For example, in all the countries artisanal fishers give part of their catch to family and friends. The amount was estimated for Sudan, Eritrea and Yemen using interviews, while for Egypt and Saudi Arabia, it was deduced based on the data from the other countries.

The approach described here can be useful to complement data gaps for traditional fishery assessment; alternatively, it can be used independently for a quick, low-cost assessment of a fishery without historic data. For effective use of the methodology, a clear definition of objective and proper preparation (e.g., adequate design of questionnaire) is important. In addition, an understanding of the culture and communication style of the society being interviewed is crucial. The scientific community and the system in general can benefit by giving due attention and respect to the knowledge available in fishers and their communities. I would like to conclude with a quote from the late Robert Johannes's book *Words of the Lagoon:*

"When it comes to understanding fish behaviour and the many environmental factors that help determine and predict it, marine biologists must often take a back seat. This is hardly surprising. There are hundreds of times as many fishermen today than there are marine biologists, and their forebears were plying their trade and passing on their accumulated knowledge tens of centuries before anyone ever heard of marine biology. What is surprising is how little effort has been made by scientists to search out and record this information"

CHAPTER 4: Catch reconstruction of the Red Sea fisheries

4.1 Synopsis

Reliable time-series catch data are fundamental for fisheries assessment and management; however, such data are usually not readily available. The catches of Red Sea fisheries are reconstructed from 1950 – 2006. Historical documents, published and unpublished reports, grey literature, databases, surveys, anecdotal information, interviews, and information on processed seafood products were used as sources. When reliable data were available for a number of years, they were used as anchor points to interpolate for missing data, based on assumptions given the best knowledge of the fisheries available. The catches of each country bordering the Red Sea are reconstructed by gear type and the catches of each gear divided according to its taxonomic composition. The reconstructed catches were compared to the catch data submitted by each country to the Food and Agricultural Organization (FAO) of the United Nations. The resulting catch trends provide interesting historical records and important guidance for the development of future fisheries management policies on resource conservation and sustaining the livelihoods of the coastal communities.

4.2 Introduction

The Red Sea has a long history (and prehistory) of resource exploitation by humans. Archaeological studies of middle stone age middens from the Eritrean Red Sea coast indicate that humans were eating giant clams and other molluscs about 125,000 years ago, possibly the most ancient such practice on record in the world (Walter *et al.*, 2000). A key part of documenting such exploitation is reporting on its catch. Given the catch level of a given fishery, inferences can be drawn on the intensity of the exploitation, and the approximate number of people involved in, and/or dependant on that fishery. Also, from additional information on the catch composition, inferences can be drawn on the technology that is deployed, the trade linkages that a fishing community has with its neighbours, its income from fishing, etc. In fact, reliable catch data are the most straightforward source of information for a variety of disciples, ranging from history and maritime anthropology to fisheries economics (Pauly, 2006).

For fisheries scientists, the value of catch data is even greater; indeed, catch data are crucial to their main task, which is to perform fish stock assessments in support of fisheries management. Herein, the key feature of stock assessments is to evaluate the status or level of fishing activity in relation to the productivity of the ecosystem, so that fish from a given stock can be caught in such a way that the various components of the system and its regeneration potential are not compromised. If such conditions are met the system will sustain fishing for a long time. To accomplish this task, there are two different subtasks to be considered: first establishing the potential of the system and second knowing where the fishery is relative to that potential. Many assessment tools have been developed to estimate the biological potential of a fishery system and use them as benchmarks for the level of exploitation. Maximum sustainable yield (MSY), and the ratio between the estimated original (un-fished) biomass and the current biomass are two of the many metrics used globally to establish levels beyond which the catch is not advised to go (Beverton and Holt, 1957; Hilborn and Walters, 1992). Of course, there are criticisms of those approaches, the assumptions they use and their applicability to different systems, and they even share part of the blame for the decline of many fisheries (Larkin, 1977; Punt and Smith, 2001). Until some better alternatives are made available to replace the traditional stock assessment tools, they will be used despite their limitations. However, while new approaches are being developed, many fisheries in the world do not have estimates of those metrics and/or are not managed at all.

Overall, reliable catch data, jointly with the methods to estimate the biomass of fish and their productivity, are crucial components of effective assessment and management of fisheries. Time series of total catch, preferably by species, is thus the most basic and important information that can be gathered about a fishery (Caddy and Gulland, 1983; Pauly and Zeller, 2003). It is even more useful when coupled with fishing effort data. Notably, catch and effort data can help with preliminary assessment of the status of population upon which fisheries depend. However, this should be done with caution (Harley *et al.*, 2001), because catch per unit of effort (CPUE), although an indicator of fish biomass, is not always proportional to abundance. CPUE can stay stable while abundance is declining, a phenomenon called ‘hyperstability’, observed on schooling pelagic fish and spawning aggregations (Hilborn and Walters, 1992; Pitcher, 1995; Sadovy and Domeier, 2005). On the other hand, CPUE can decline more than the actual decline of abundance called ‘hyperdepletion’ (Hilborn and Walters, 1992). This can happen, for example, when only a portion of the population is vulnerable to the fishery (Walters and Bonfil, 1999; Kleiber and Maunder, 2008). However, for many fisheries, CPUE is the best type of information available for assessment, and not using it is short-sighted.

There are many ways catch data can be collected. The most common are log books filled in by the fishers, observers onboard the fishing vessels and data collection at the landing sites and from markets (e.g., auction and exports). For the Red Sea countries, many of these methods are very difficult to implement. Most of the local (artisanal) fishers cannot write. The communities are predominantly based on oral traditions, so log books are out of question. The majority of the boats are small, thus on-board observers are impractical to deploy. Data recording at landing sites, although still arduous, is the most practical way for routine catch and effort data collection. The challenge with that is that the number of landing sites along the coast is quite big, and some of them are not even known to the fisheries administrations. Setting up proper data collection systems is not straightforward, given the complexity of fisheries and fish marketing. There are many fates of a fish following its encounter with fishing gear (Figure 4.1). For some Red Sea countries, more than half of the fish catch does not go through fish market, where official recording occurs (Chakraborty, 1983). Thus, proper planning and systematic collection procedures are needed (Gulland, 1975; Sparre, 2000). This requires resources, so developed countries usually have better catch and related statistics than developing countries (Alder *et al.*, 2010), while the latter also have to contend with a generally higher biodiversity, which makes the catch highly diverse, and hence comprehensive catch statistics difficult to produce (Pauly and Watson, 2008). Note as an aside the irony that even in developed countries with better statistics, overfishing is rampant, e.g., in the North Atlantic (see e.g., Christensen *et al.*, 2003).

The Food and Agricultural Organization (FAO) of the United Nations compiles and distributes global data on fisheries since the late 1940s, issued annually since 1950 (Garibaldi, 2012; Pauly and Froese, 2012). Garibaldi (2012) gives a comprehensive description of the FAO database and its evolution. Data submission to FAO is based on voluntary reports by member countries, which are required to send annually updated accounts of their fisheries catches to the FAO Statistic Division, which standardizes them to a set format, and incorporates them in their publicly available global database of fisheries statistics (see http://www.fao.org/fishery/statistics/en; (Pauly and Zeller, 2003). Because it consists of continuous, long time series and is easy to access, the FAO database is used extensively to guide local, regional or international decisions in countries where local data recording systems are lacking, such as the Red Sea countries. Especially for regional and international analyses, it has been heavily used (e.g., 600 refereed journals cited the FAO database in the last 15 years) because its standardized data makes comparisons straightforward (Garibaldi, 2012).

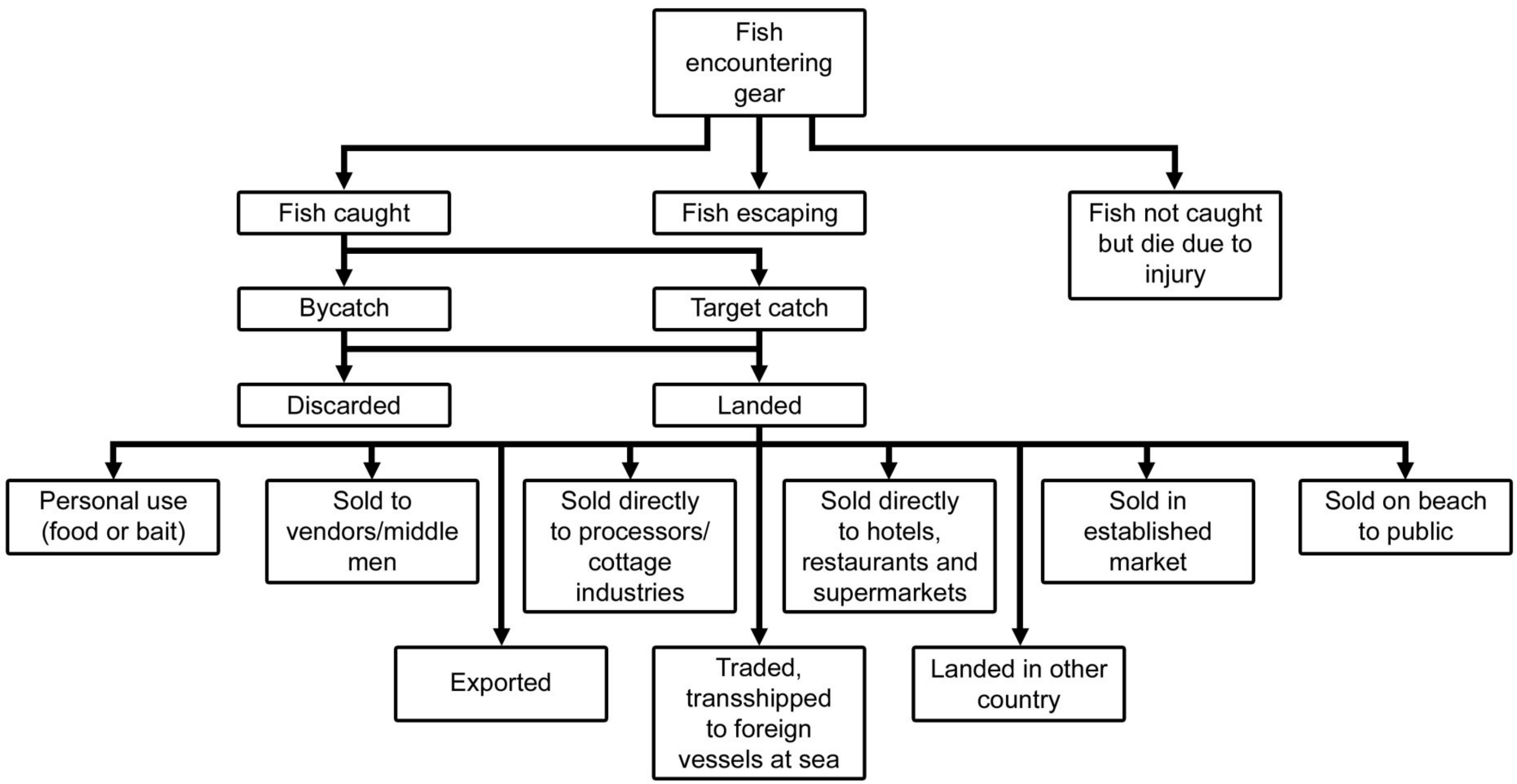


Figure 4.1 The fate of a fish since its first encounter with a fishing gear, (Based on Mohammed, 2003).

FAO's mandate is very broad, and when it comes to fishery data, it can only compile what is submitted to it. This is the main bottleneck to the quality of the data. Countries do not necessarily have the incentive to submit reliable data, except as moral obligation to contribute to a global system. Thus, it is not uncommon for countries to send incorrect fishery data records (Pauly and Froese, 2012), and FAO does not have a legal or procedural mandate to refuse such data. Even more problematic, the technical reports produced by FAO itself are not reflected in the database. Thus, the global estimates of discards documented in successive *Technical Papers* and other FAO documents were never included in the FAO statistics (Zeller and Pauly, 2005), even though you can only discard fish that have been previously caught. Another example, applying specifically to the Red Sea, is that most of the early fishery data for the Red Sea comes from national or regional projects executed by FAO, especially the project 'Development of fisheries in areas of the Red Sea and Gulf of Aden', which ran from the late 1970s to the mid-1980s. Through the agreements in those projects, FAO would send staff or consultants to assess the national fisheries and recommend their future developments. Among other things, the projects surveyed the fisheries and estimated the effort and catch (Chakraborty, 1984), but these results were not incorporated into the FAO catch database.

Moreover, while the countries around the Red Sea are all members of FAO, and hence they send their fishery data to FAO, many suffer from political and institutional instability, which affects their fishery agencies, and thus there are gaps and inconsistencies in the data supplied to FAO. FAO's mandate, while broad, does not include detailed analysis and review of the data supplied by member countries, which thus remain limited in their reliability and usefulness. Data submitted to FAO by over half of the developing and a quarter of developed countries is not of good quality (Garibaldi, 2012). The following are the major constraints with the fishery statistics in the FAO database. These issues are not specific to the Red Sea countries, but affect the database in general.

1. The FAO database reports global marine catches spatially only to the extent that they are allocated to 19 giant 'statistical areas'. In the cases of Red Sea catches, this is area 51, the 'Western Indian Ocean', extending from the tip of the Gulf of Suez in the North to the Antarctic Convergence in the South, and from Sri Lanka in the East to South Africa in the West;

2. The level of taxonomic aggregation of the catch is usually very high, and a large part of the catch is reported as 'miscellaneous' or unidentified species, which masks qualitative changes occurring in the ecosystem;
3. The member countries often send catch data to FAO (usually emanating from a Department of Fisheries or similar institution) through their Ministry of Trade, or some central statistics office or other government agency not directly connected with fisheries, where they are often over-aggregated and/or otherwise modified before being sent off;
4. Some countries may have political reasons to misreport their catch, including over-reporting of catches for political reasons as China did to FAO for at least two decades (Watson and Pauly, 2001) and, gravest of all;
5. When data for certain fisheries are not available (because the fisheries in question were not monitored), no estimate for the missing catch data are submitted. Subsequently, absent catch data for a given year become an annual catch of precisely '0' tonne. Thus, the FAO database does not account for illegal, unreported and unregulated (IUU) catch (Alverson *et al.*, 1994; Kelleher, 2004).

The use of FAO fishery data by many organizations will not stop anytime soon, and neither should it, but one can hope that such use becomes more critical (Pauly and Froese, 2012). Also, there is at least one research project initiative, the *Sea Around Us* project (www.seaaroundus.org), which aims to improve the quality of the global marine fishery data. As a university-based research project, it is not limited by legal procedures, as the FAO is to its members. Hence, country catch reports are criticized, scrutinized, alternative sources are used, and when data are missing, they are estimated with transparent assumptions given the best knowledge of the fishery available at the time. In effect, the major issues with the FAO database can be overcome through reconstructing historical catch time series (Pauly, 1998; Pauly and Zeller, 2003; Pauly and Froese, 2012). Reconstructed time series of catch (and effort) data from the past are not merely useful for historical purposes. Rather, they provide a basis for overcoming the shifting baseline syndrome (Pauly, 1995), i.e., for accurate assessment of the impact of fishing on marine ecosystems, and for ecological restoration (Scott Baker and Clapham, 2004; Pitcher, 2005). The lessons learned from catch reconstruction in different circumstances of the fisheries can be informative, similar to 'scenarios' in adaptive management of resources (Walters, 1986).

Catch reconstructions, which can be performed at any scale, allow for the effect of items (1) to (5) in the above to be mitigated. Thus, for example issue (1) was addressed here by reconstructing the catch of Yemen within the Red Sea separately from that in the Gulf of Aden, which are in the same FAO area. There is a similar issue with the west and east coast of Saudi Arabia. Item (2) is addressed by identifying and researching the fisheries (including the gears) which generated all catches, which usually allows a reduction of the unidentified components of the catch.

Catch reconstruction involves quantifying the catch of each fishery known to have existed, based (when 'hard' catch data are not available) on the 'shadow' that this fishery throws on the society in which it is embedded. This shadow may consist of household fish consumption figures, number and income of fishers, export figures, etc. (Pauly, 1998). In either case, when item (3) above leads to cases of item (5), catch can be estimated; these estimates, while approximate, will generally be closer to reality that the precise estimate of zero in the official databases (Pitcher *et al.*, 2002; Zeller *et al.*, 2007).

The main objective of this chapter is to reconstruct catches of the Red Sea fisheries from 1950, the year FAO started to publish annual statistical reports on the fisheries of the world, up to the most recent fishery statistics data available. Included here are all the Red Sea countries: Egypt, Sudan, Eritrea, Yemen, Saudi Arabia, Jordan and Israel and all the fishing sectors of these countries. Jordan and Israel have very short coastlines in the Red Sea in the inner Gulf of Aqaba, i.e., they do not have major fisheries in the Red Sea. Thus, this analysis will be driven by data from the other countries, though data from Jordan and Israel are also included. The output will be a time series of standardized fishery catch for the Red Sea, divided by sector, gear and catch composition.

4.3 Materials and methods

The main methodology in catch reconstruction is digging into different sources reporting the catches of the countries, critically analyzing them, and organizing them to a common standard, which can be used for comparison and carrying out analysis for the assessment of the resources. The sources include peer-reviewed published papers, grey literature (mainly government, consultant, and FAO reports), and national databases complemented by field trips to Egypt, Sudan, Eritrea, and Yemen from December 2006 to September 2007. The information collected was enriched by the insights of local experts and colleagues who provided data through personal communications. The catch reconstruction for the whole Red Sea was first compiled in the form of individual country reports, co-authored by country experts: Egypt (Tesfamichael and Mehanna, 2012), Sudan (Tesfamichael and Elawad, 2012), Eritrea (Tesfamichael and Mohamud, 2012), Yemen (Tesfamichael and Rossing, 2012a), Saudi Arabia (Tesfamichael and Rossing, 2012b), and Jordan and Israel (Govender and Pauly, 2012). In them the specific details of the reconstruction for each country are given. Here the summary of the general methodology and the procedure to establish one coherent data set for the whole Red Sea are described.

4.3.1 Sources

A continuous database of fishery catch, starting from 1950, does not exist for any of the Red Sea countries and had to be assembled from different sources. The earliest data sources for the Red Sea countries were technical reports of the assessments of the fishery resources for planning the development of the fishing industry, starting in the decades following WWII. The 1950s was also a period where several of these countries became independent and started to run their national economies, and food security became a critical issue. These assessments/surveys were made by foreign experts (except for Egypt), who were usually recruited through FAO. The earliest sources available were for Saudi Arabia (El-Saby and Farina, 1954), Sudan (Kristjonsson, 1956), Eritrea (Ben-Yami, 1964), Egypt (Al-Khol and El-Hawary, 1970) and Yemen (Lisac, 1971; Losse, 1973). Some of the early assessment work was done through bilateral arrangements or consultants hired directly by the countries (e.g. see Ben-Yami, 1964; Atkins, 1965; Grofit, 1971 for Eritrea). In the 1970s and 1980s, in part because of the Cold War and ensuing East-West competition, development aid was pouring into the Red Sea countries and a fraction of that was assigned to fisheries development. A regional project for the Red Sea area, ‘Development of fisheries in areas of the Red Sea and Gulf of Aden’, was carried out from the end of the 1970s until the mid-1980s and led to an improvement of the quality (comprehensiveness and taxonomic resolution) of fishery catch data. Additional sources were also used, notably tax offices and export records. For example, the catch of the Eritrean beach seine small pelagic fishery was reconstructed from export figures for fish meal, which was the output of the fishery (Ben-Yami, 1964).

Organized databases and/or annual fishery statistical reports are a relatively new development for the Red Sea countries. The oldest database is that of Egypt, which starts in 1979, while Saudi Arabia started publishing its annual fishery statistics in the 1980s. Eritrea has had annual reports since its independence in 1991, but an organized database started only in 1996. Sporadic annual reports are available for Yemen and a database system is being established. Sudan does not have any fishery data reporting system yet; however, daily catch data are collected at the main fishing market of Port Sudan, which are stored, but not issued as annual reports. All these sources were accessed for the catch reconstruction of the respective countries.

Once the sources were accessed, they were analyzed for their spatial, temporal and sectoral coverage. Some reports were written only for a certain section of the countries or only a specific sector of the fisheries. Then the sources were critically examined with regards to the method(s) and assumptions used in collecting their data. Only after the data were scrutinized were they used for catch reconstruction. For some years, data were available from different sources, some simply regurgitating previous reports. In such cases an effort was made to locate the original reports. When there were multiple independent sources, the ones which have detailed explanations of the methodology and comprehensive coverage were selected. In a few cases, the information from one source was used to correct data from another report.

4.3.2 Interviews

Interviews were conducted with fishers ranging from 15 – 82 years in age, and with fishing village elders and the employees of fisheries administrations. The main goal of the interviews was to assess long-term change in fisheries productivity using fishers' memories. A separate analysis of the interview data is given in Chapter 3, but with respect to catch reconstruction, interviews had two major aspects. First, they were very useful in filling data gaps. For some periods there were no records at all, so interviewees were asked to explain what happened in those periods and whether the catches were higher, lower or about equal to the adjacent periods with records. The other type of information supplied by the interviews was the amount of unreported catch, i.e., the catch missed by official records. For many artisanal fisheries in the Red Sea, this included the amount of catch given freely to some members of the community and the catch landed at remote landing places, where there are no data collectors. Regarding the former, there is a strong tradition, shared by the maritime cultures of Red Sea countries, that part of the catch is expected to be given freely to family, friends and people who need assistance (e.g., the elderly, disabled, and widows…). The amount given freely is called *'kusar'* and is a form of food security social network. Not to give *'kusar'* leads to loss of prestige, which may have serious consequences, e.g., with regards to market transactions and eventual marriages. The amount was about half of the total catch in the 1950s and 1960s; however, as the catches started to decrease and the fish accrued market value, the proportion of the catch devoted to *kusar* started to decrease.

The second useful input from the interviews was explanations of discrepancies among reports. The insights from older fishers and people who have been involved in the management of fisheries for a long time were able to explain ambiguities in reports and other records. Although they did not give specific quantitative values, their ability to give comparative qualitative information helped to base the assumptions used in quantifying the catch.

4.3.3 Missing data

For the years data were missing, interpolations or extrapolations were made to fill in the data gaps. These were made on the basis of explicitly stated assumptions, given the best knowledge of the fisheries available at the time. Population size and per capita consumption were also frequently used as a proxy, to infer catches.

4.3.4 Compilation

Once the catches were reconstructed for each country, they were added together to represent the catches of the Red Sea as a whole. This addition was made in the way that appeared most informative, i.e., by fishing sector (industrial or artisanal) and by gear types. Then, the catch composition was calculated for each gear category. Dividing the catch by sector and gear is based on practical uses of the information. Almost all countries divide their fishery into artisanal (a long traditional fishing practice), and industrial, which is usually operated by foreign fleets, except for Egypt (for a long time) and Saudi Arabia (only recently). These two sectors are different in their economic and cultural settings, and conflicts between the two are common (Pauly, 2006). Gears reflect the technical aspect of human interaction with the resources, and thus can serve as management units (Tesfamichael, 2001), as also used in the ecosystem model of the Red Sea (see Chapter 6). The main gears, based on their contribution to total catch are: handlining, gillnet and beach seine fisheries in the artisanal, and trawl and purse seine gear in the industrial sectors.

The catches of each country were divided by the fishery administrations of the countries into artisanal and industrial, but not by gears for all countries. When catches were not divided by gear, the taxonomic groups were allocated to a specific gear based on the life history and habitat of the species, following the classification of global fisheries performed by Watson *et al.,* (2006). For example, in the artisanal fishery, small pelagic species are categorized under beach seine, carnivorous coral reef fishes under handlining and large pelagic under gillnet. The Eritrean catch was already divided by gear, while the Sudanese catch was presented in the categories 'artisanal', 'trawling' and 'purse seining'. Since the artisanal fishery in Sudan is predominantly handlining, all of it was categorized under handlining. The Egyptian catch was divided by gears for the industrial sector, but not for the artisanal catch; this was here divided into gillnet and handlining based on the species composition of the catch and qualitative description of the fishery. The Yemeni industrial fishery is all trawling, but the artisanal catch needed to be divided into handlining and gillnet. Here, account was taken of taxonomic groups that were caught by both gears, namely barracudas and breams; their catch was divided equally between the two gears. The Saudi artisanal catch was originally not divided into gears, but most of the catch was from handlining (Sakurai, 1998; MAW, 2000, 2008), so all taxa could be allocated to handlining, except species which are predominantly pelagic and known to be caught mainly by gillnet (Spanish mackerel, tunas, Indian mackerel, queenfish and mullets). The Saudi industrial fishery catch was not divided by gears either. This was done based on the composition of the catch. For all countries, the catch of trawl was divided into retained and discarded catch. The latter can be very significant proportion, usually ignored in the data recording systems. The division was necessary because the taxonomic compositions of the retained and discarded catch are different. Gears with very small contribution to the total catch and unidentified groups, which cannot be assigned to any gear due to lack of taxonomic resolution were placed under 'uncategorized catch' (Appendix A1).

4.4 Results and discussion

The total reconstructed catch was different from the data submitted by the countries to FAO, and in most cases, the reconstructed catch was higher (Figure 4.2). Overall, from 1950 – 2006 the total catch taken from the Red Sea is 1,312,259 t or 34% higher than suggested by the FAO database. In the following, a brief per-country account is given, starting with Egypt and moving counter-clockwise along the Red Sea coast.

For Egypt, the reconstructed catch is higher than the fisheries catch statistics that Egypt submits to FAO from the beginning of 1960s until the beginning of 1990s, but the reverse after the mid 1990s. This discrepancy may be due to the fact that Egypt fishes outside its own waters (e.g., in Eritrean waters starting early 1990s (Tesfamichael and Mohamud, 2012) and these catches are not included in the reconstruction (Tesfamichael and Mehanna, 2012), as the objective of the reconstruction is to quantify the amount fished in the waters of various countries, and not where they landed. The catch of Egyptian vessels from Eritrean waters is reported in the reconstruction of Eritrea.

The Sudanese data submitted to FAO does not include catch of the shell (trochus and mother-of-pearl) fishery, which was very important before 1980s. Hence, in Figure (4.2), the reconstructed catch without shells is presented (along with the total) to enable comparisons. Generally there is no large difference between the reconstructed data and data submitted to FAO for Sudan. The sudden spike of Sudanese catch reported to FAO in 1983, on the other hand, is likely due to a reporting error, as there was no major change in the fisheries likely to cause such a sudden jump for only one year. The higher catches reported to FAO after the 1990s are suspicious, as the locally available data do not indicate such a high level of total catch (Tesfamichael and Elawad, 2012).

For Eritrea, Yemen and Saudi Arabia, the reconstructed catches are higher than those reported to FAO (Figure 4.2), due to the latter not including various fisheries and omitting discards. The major discrepancies between the reconstructed data and data submitted to FAO for Eritrea are in the early decades (1950s and 60s) and later after 2000. In between those periods the fishery was not active, hence catches were low (Tesfamichael and Mohamud, 2012). For Yemen in the Red Sea, the reconstructed catch is continuously higher than reported catch, the difference being more consistent for Yemen than for any other country. It shows a continuous omission of part of the catch in the reporting system (Tesfamichael and Rossing, 2012a). There is clear difference between the reconstructed and reported catch for Saudi Arabia in the Red Sea until the mid 1980s. After the mid 1980s the Saudi fishery became more industrialized with trawlers, and the gap between the two data sets is mainly the discard (Tesfamichael and Rossing, 2012b). The reconstructed catches of Israel and Jordan are negligible compared to those of the other countries (Govender and Pauly, 2012), which is understandable given their minuscule footholds in the inner Gulf of Aqaba. They also exhibited less fluctuation than the FAO data. Overall, Egypt and Yemen are the heavyweights of the Red Sea fisheries, followed by Saudi Arabia. Sudan has the lowest catch once Israel and Jordan are discounted

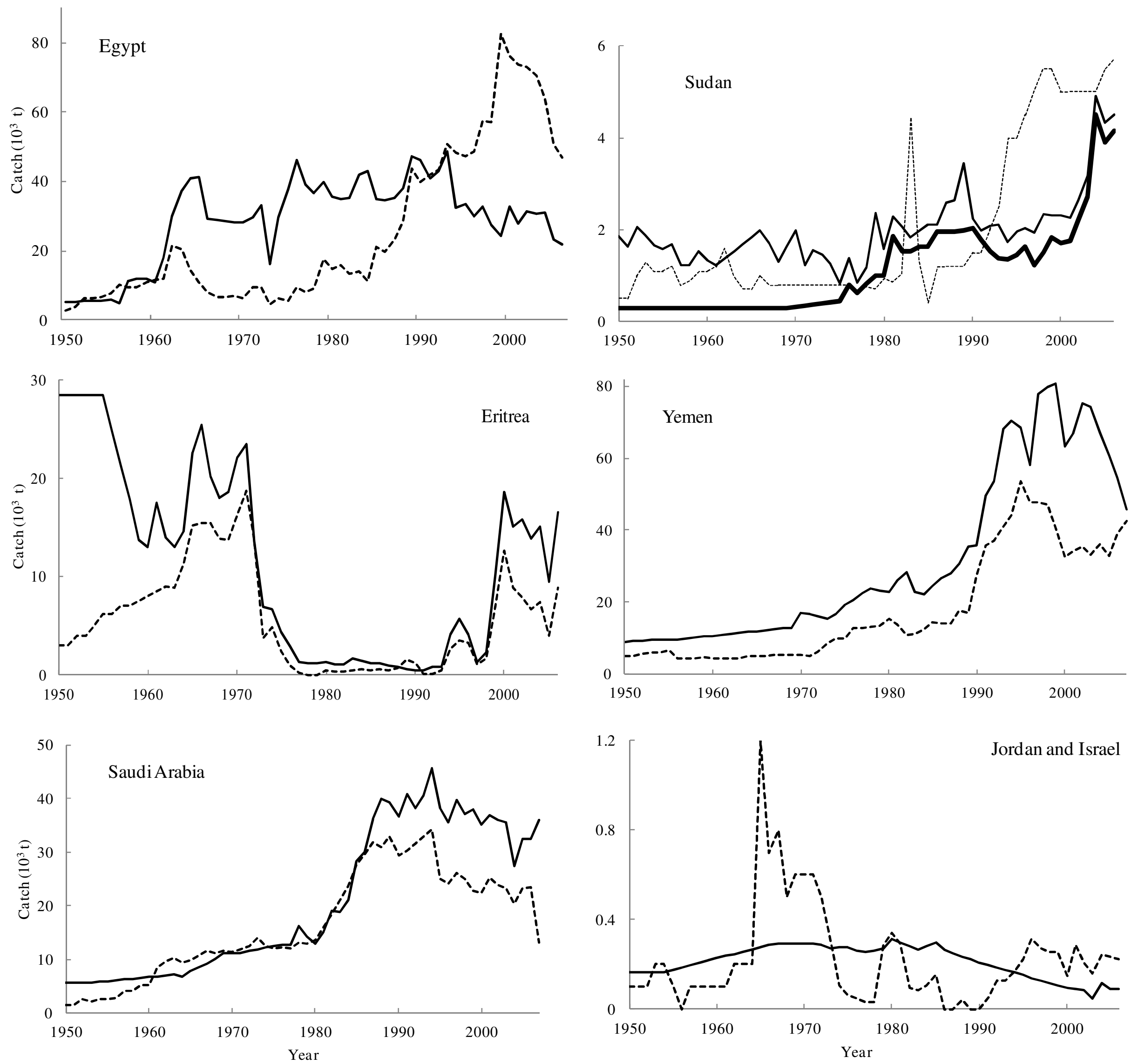


Figure 4.2 Total reconstructed catch (solid line) compared to the data submitted by the Red Sea countries to FAO (broken line). As the Sudanese FAO data do not include shellfish, a version of the reconstructed catch not including shellfish is also included (thicker line). Note: Y-axes have different scales.

Based on the reconstructed catch, the contribution of the artisanal fishery to the total catch in the Red Sea is higher than the industrial sector (Figure 4.3) Thus, from 1950 – 2006 the artisanal was more than 2.5 times the industrial catch. This has major economic and social implications. Artisanal fisheries employ a higher number of fishers per tonne of catch (Pauly, 2006), which translates to higher employment and livelihood in the communities. Note that the industrial catch in Figure (4.3) does not include discards, which are not landed and do not have any economic value; however, they are important ecologically, hence are reported in Figure (4.5). The major increase in the total catch of artisanal fisheries happened in the mid-1980s, the time when motorization of local boats started gaining momentum.

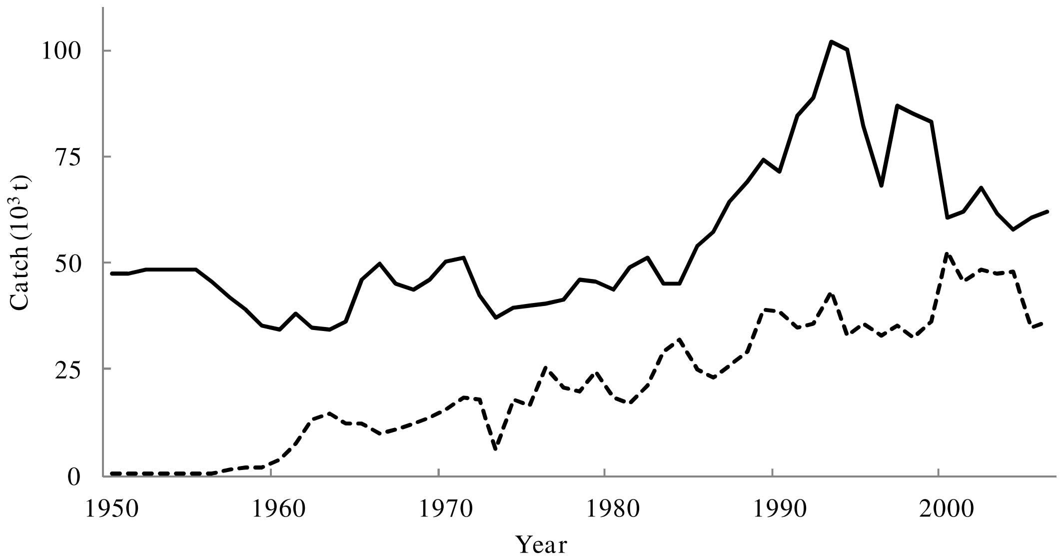


Figure 4.3 Total reconstructed landed catch of artisanal (solid line) and industrial (broken line) fisheries for the Red Sea.

In the artisanal sector, the major fisheries are handlining, gillnet and beach seine. The contribution of handlining is the highest followed by gillnet. The catch composition of the gears is usually very diverse. However, a few taxonomic groups dominate (Figure 4.4). For better graphic presentation, all the minor groups are lumped together under 'others', while the detailed catch compositions by gear are given in Appendix (C.2 – C.8). Sharks are caught by deepwater gillnet and handlining, but the shark fishery is treated separately because of its unique importance (Bonfil, 1994; Bonfil and Abdallah, 2004), in particular because of the singular life history of sharks (Frisk *et al.*, 2001), and high demand for sharks i.e., for shark fins (Fong, 1999; Biery and Pauly, 2012). Indeed, this study shows that shark suffered the worst decline in the Red Sea (see Chapters 2, 3 and 6). The sharks' catch by countries is given in Figure (4.4), which shows that the catches of sharks from Egypt and Sudan are negligible compared with those of other countries.

For non-shark handlining and gillnets, the catches started to increase in the mid-1970s, reaching a peak in the early 1990s and then declining. On the other hand the catch of the beach seine fishery was higher in the earlier years and declined later, mainly due to the collapse of the fish meal industry in Eritrea because of political instability (Tesfamichael and Mohamud, 2012).

As in the artisanal sector, the catch composition of the industrial sector is also dominated by a few taxonomic groups (Figure 4.5). The catch of trawlers was low until the 1990s, when the industrial fishery of Saudi Arabia became well established (Tesfamichael and Rossing, 2012b) and Egyptian trawlers were operating widely in other countries' waters (Tesfamichael and Elawad, 2012; Tesfamichael and Mohamud, 2012). The purse seine fishery is almost exclusively Egyptian and has been active for a long time (Rafail, 1970, 1972), operating mainly in Egyptian waters and the northern part of Sudan (Tesfamichael and Elawad, 2012). The fishery started with few purse seiners (Rafail, 1972) and their numbers increased gradually resulting in increased catch (Barrania and El Shennawi, 1979; Sanders *et al.*, 1984a). The decline of the purse seine catch after its peak in 1992 appears to be due to a decline in the number of trips per year carried out by the vessels (GAFRD, 2010).

Despite the above, no attempt is made in this chapter to draw inferences on the state of the fisheries resources. Such an attempt is made in Chapter 6, using an ecosystem model of the Red Sea which incorporates the catch data presented here, and time series of fishing effort aggregated by gear type.

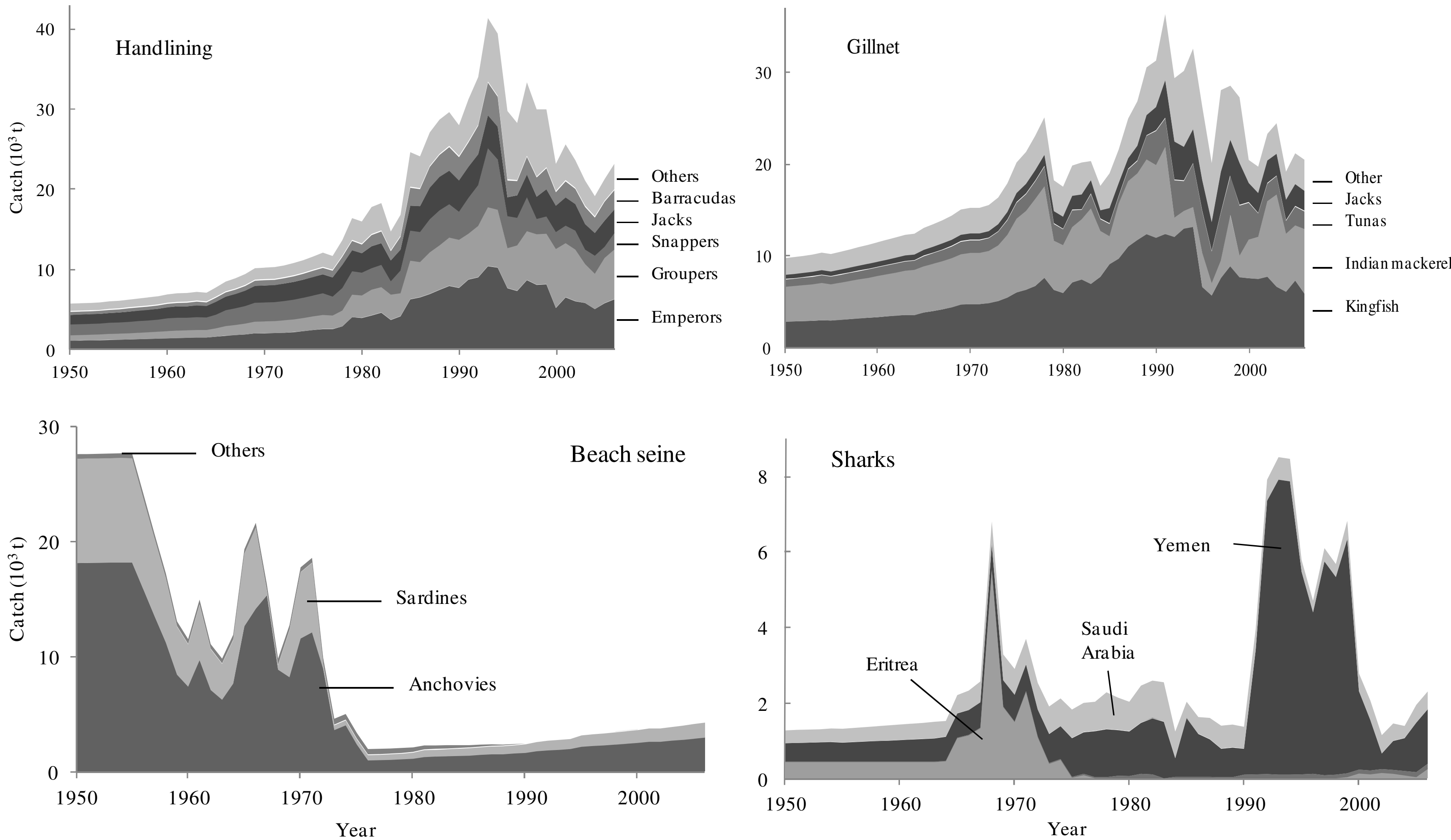


Figure 4.4 Catch composition of major artisanal fisheries of the Red Sea.

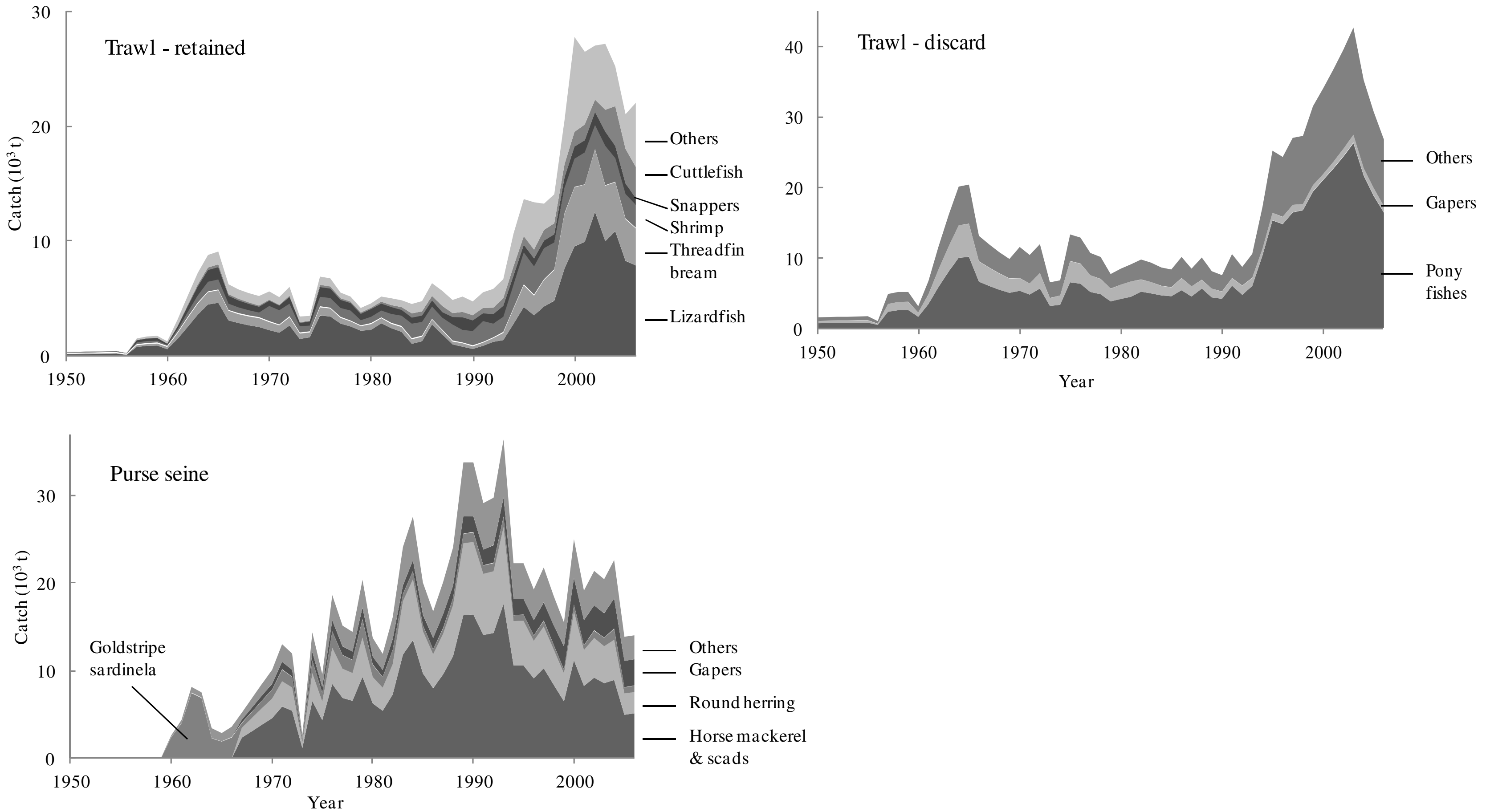


Figure 4.5 Catch composition of Red Sea industrial fisheries.

CHAPTER 5: Estimating the unreported catch: a case study of Eritrean Red Sea fisheries

5.1 Synopsis

Unreported catch from three major fisheries in the Eritrean Red Sea is investigated in order to estimate the impact of the total extraction of fish from the ecosystem, which will help the assessment of the resource and its management. The fisheries target small pelagics, demersal finfish and shrimps, and were chosen for their major contribution to the total Eritrean catch, economic importance and/or significant contribution to unreported catch. The analysis is carried out from 1950 – 2004, subdivided into blocks of 5 years. Factors that provide incentives to fishers to misreport are obtained by examining the historical development of the fisheries. The analysis is based on interpolations, guided by the incentives, between independent quantitative estimates of unreported catch ("anchor points"). Errors are estimated using a Monte Carlo sampling technique. The fishery industry in Eritrea operated smoothly from the mid 1950s to the end of 1960s, when it was disrupted by political instability. Fishing operations were normalized again at the beginning of the 1990s. Of the three fisheries, the small pelagic fishery has the least unreported catch; a maximum of 5% of the total extracted. The total catch from the three fisheries has been under-reported on average by 21%.

5.2 Introduction

Much fisheries research used in decision-making depends on data that are acquired from the fishery industry itself. For example, quota setting using virtual population analysis (VPA) depends on catch data from the fishing fleets (Shepherd and Pope, 2002). However, catch officially reported to fishery organizations is generally not the amount extracted from the ecosystem (see Figure 4.1 in Chapter 4). Some of the fish caught are discarded because they have low or no economic value, some are not reported, or are reported as something else, because the fishing operation is illegal, while others are not recorded simply because they are not regulated (Pitcher *et al.*, 2002). If these components of fishing activity are not included in the catch analysis, actual extractions will be underestimated, encouraging the notion that more is still available to be fished. This may result in severe depletion or even extirpation or extinction of species. The effect of unreported catches can be worse when parameters estimated from the catch are used in other analyses, where errors will have a compounded effect. The magnitude of unreported catch can be very big; for example in shrimp fisheries discards are usually more than the retained catch, in some cases by an order of magnitude. So, the closer we can get to the actual amount extracted, the better will be the inferences we can make about the status of a fishery.

With the exception of discards in those countries with an observer system, e.g., USA (Harrington *et al.*, 2005), estimates of unreported catch are not available in the official reports of many countries. The challenge is, therefore, to estimate what is not reported but is known to be taking place. Estimating unreported catch in the form of discards has been receiving more attention. Based on data from the late 1980s, Alverson *et al.,* (1994) estimated the global unreported discards to be 17.9 to 39.5 million tonnes per year, while the maximum global catch given by the Food and Agricultural Organization (FAO) of the UN was around 85 million tonnes in the mid 1990s. Starting in the early 1990s discards decreased because of technological innovation, better management and increased utilization of catch. Using data from 1992 to 2001, Kelleher (2004) estimated global discards to be 7.3 million tonnes. Though the decline of discards is a good sign of effective use of extracted marine resources, the overall decline of total catch (landing and discarding) at a steeper rate than previously thought is a serious concern

(Zeller and Pauly, 2005). Besides discards there are also illegal and unregulated fishing activities, which are not reported. Pitcher *et al.,* (2002) estimated unreported catch from the different sources in Morocco and Iceland based on knowledge of the development of the fishery and some clues about the unreported catch. Similar methodology with some minor refinement for British Columbian fisheries is used in Ainsworth and Pitcher (2005). Patterson (1998) explored the effect of misreporting on parameter estimates by comparing stock assessment models that use catch reports and estimates made from survey data only.

Estimating unreported catch is tricky as it deals with what is known to happen but no data are given, hence the term 'unreported catch'. In the absence of data records, it is not uncommon for researchers to depend on information gained from people knowledgeable with the system and the issue being investigated. For example, oral traditions have been a valuable source of information about historical events in fisheries (e.g., Neis *et al.* 1999; Sáenz-Arroyo *et al.* 2005). See also Chapter 3 where interviews are used to analyze long-term trends in catch rates. Pauly (1995) argues when there is no data record, anecdotes can be "as factual as temperature records". Sometimes the only information available is expert or traditional knowledge, and not using it may mean putting the fisheries at risk (Johannes *et al.*, 2000). In many fishery analyses, unless unreported catch is accounted for explicitly, it is implicitly assumed to be zero, which is misleading and unacceptable (Pitcher *et al.*, 2002). Patterson (1998) found that estimates of fishing mortality were imprecise when catches were under-reported off the coast of west Scotland. Bias from subjectivity provides a caution about using "expert" knowledge or judgment in fishery analysis, but it is not a good reason not to use it at all. Error due to subjectivity, which is present in almost any observation, can be systematically minimized and can be acknowledged by reporting error ranges explicitly.

In this chapter I estimate the unreported catch based on expert judgments, guided by influences to misreport in the history of the fishery and by independent quantitative estimates of unreported catch as "anchor points". From these anchors, estimates are interpolated for the years when quantitative data are not available. I used Monte Carlo simulation to determine unreported catch and the error range for three fisheries from the Eritrean coast of the Red Sea.

The Eritrean fishery in the Red Sea is a typical tropical fishery, multi-species and multi-gears. It can be categorized into small-scale artisanal and large-scale commercial fisheries. The artisanal fisheries are characterized by selective gears operating in shallow coastal water on coral reefs. The commercial fisheries use more powerful vessels and operate in deeper waters. The small-scale fisheries, which are mainly handlining and gillnet, are not included in this research because they use selective gear, hence discards are very small, and their catches are well recorded as there are a very few fish landing sites where almost all the catches are landed, and they are well monitored.

Based on operation and management, the Eritrean fisheries can be divided into two clear periods: before and after the independence of Eritrea from Ethiopia in 1993. The industry was larger before independence, starting from the mid 1950s until the end of the 1960s, and was dominated by a small pelagic fishery for fish meal exported to Europe and Asia (Sanders and Morgan, 1989). There was no strong management or fish landing data collection as it was only a small branch of a bigger government body stationed far away from the coast. The most important data available were the amount of fish meal exported, kept for tax purposes. After independence the fishery started to gain momentum, following a complete destruction of its infrastructure during the independence war. Nowadays, the commercial sector is mainly dominated by trawl fisheries. There is a stronger management and data collection system. Fish landings are monitored by the Ministry of Fisheries. The fish landing sites are very few, which makes the monitoring easier.

Three fisheries are included in this chapter. They were selected based on their contribution to the total catch (they account for more than 80% of the total catch), economic importance and/or for being known to have a relatively high contribution to the unreported catch. The three fisheries also have relatively better data records and there are some independent estimates of unreported catch either from surveys or onboard observations. They are:

Small pelagic fishery

This beach seine fishery was the most important fishery in the 1950s and 1960s especially for its volume, accounting for up to 90% of the total reported catch (Grofit, 1971). Its main target species were sardines (*Herklotsichthys quadrimaculatus*) and anchovies (*Encrasicholina heteroloba* and *Thryssa baelama*) used mainly in the production of fish meal, which was exported to Europe and Asia. A small proportion of the catch was sun-dried for human consumption for markets in Asia (Sanders and Morgan, 1989). Since the catch was used for fish meal production, nothing was discarded; however, there was some misreporting. Relatively, it was a well-documented fishery but its infrastructure was dismantled before Eritrean independence, and this fishery no longer exists despite the continued presence of its target species.

Finfish trawl fishery

Bottom trawls for finfish, operating on both hard and soft bottoms, are important fisheries both before and after 1993. They are operated almost exclusively by 25 – 40 m long foreign vessels, mainly from Egypt and Saudi Arabia under joint venture, with enough power to trawl in deeper waters (450 – 1500 HP). Since 1993 this fishery has provided the largest contribution to the total catch. The dominant species in the catch are lizard fish (*Saurida undosquamis* and *S. tumbil*) and threadfin bream (*Nemipterus japonicus).* The unit price of these fishes is not very high, but large catches make it economically worthwhile. This fishery has intensive grading and huge discarding.

Shrimp trawl fishery

This trawl fishery does not make a big contribution to the total catch; however, it is very lucrative because of high prices in the market. It operates only in soft bottom and has a large amount of discarding. Its operation, mainly by Egyptian and Saudi trawlers, has been sporadic. Its total catch has never been as high as the estimated maximum sustainable annual yield of 500 tonnes (Giudicelli, 1984). The species commonly caught are: *Peneus semisulcatus*, *P. japonicus* and *P. latisulcatus.*

In this chapter only the total estimated unreported catch is given. It comes mainly from one component: "misreporting" for the small pelagic fishery and "discarding" for the other two fisheries. As part of the agreement with the trawl fishery, observers are sent with the trawlers, especially after 1993. The source of unreported catch in these fisheries is, therefore, mainly from discarding and not from misreporting or illegal operation. Some rare incidences of illegal fishing are known to happen, however the amounts are likely insignificant.

5.3 Materials and methods

In the absence of quantitative data on the unreported catch, I used qualitative ranks or categories of "incentives to misreport" based on expert judgments and qualitative descriptions of the fisheries in published and unpublished reports. The categories are high, medium/high, medium, low/medium and low. These categories are used in order to have the same standards as all previous similar researches. The categories are converted to quantitative values using anchor points.

The procedure starts with a time series of the reported catch, which was obtained from the Ministry of Fisheries, Eritrea and other records. Though FAO has a global database of fishery catches, data on reported catch was sought first from Eritrea, as the accuracy of the FAO catch data is questionable (Watson and Pauly, 2001; Pauly and Zeller, 2003). An extensive search of published papers, reports and expert consultation allowed to construct the catch from 1950 – 2004. This case study was carried out in 2005, before the catch reconstruction (Chapter 4) to try out the unreported catch estimation method. It covers the period from 1950 – 2004, while the catch reconstruction, which includes unreported catch, goes from 1950 – 2006. This chapter shows how detailed analysis of unreported catch and uncertainty analysis can be done.

Table (5.1) shows the reported catch of the three fisheries included in this chapter. Since the analysis is made in blocks of 5 years, the catch is the average over the 5 years. The catch after

1993 was obtained from a database maintained by the Ministry of Fisheries Eritrea (MOF, 2007), which is well-organized and even has estimates of unreported catch for trawling. The catch of small pelagic species in the past was estimated from export of fish meal (Ben-Yami, 1964; Grofit, 1971).

The next step is to get the qualitative categories of incentives to misreport catch. Though the categories for each 5 year block can be acquired directly from expert opinions and/or inferring from qualitative descriptions in reports, I guided the ranking by tabulating the major developments in the fisheries that could influence the incentive to misreport. These guidelines minimize the subjectivity in the ranking. The development of the fisheries through time was investigated to pinpoint changes that would influence the fishers to misreport their catch. The changes can be technical (e.g. change in catching power), economic such as markets and prices, changes in the management scheme, and political or any other change. An extensive literature search and expert opinions were used to document changes in the fisheries, and a table showing the influences on the incentives to misreport was prepared (Table D.1 in the Appendix). It is important to note that these influences are by no means complete; however, they capture the major changes in the fisheries which could affect reporting. The table also shows if the influences have a positive or negative effect on the incentives to misreport. Established facts in fisheries sciences were applied, when appropriate, to evaluate the effects of influences on the incentives to misreport. For example, using smaller mesh size at the cod-end of a trawl net increases discard amounts.

Once the table of influences is prepared, the qualitative categories of incentives to misreport are established (Table 5.2) based on those influences. I acknowledge that the expert judgments used in this part can be the most subjective part of the procedure. However, expert judgments are valuable and sometimes the only information available for estimating what is not reported (Pauly, 1995; Johannes *et al.*, 2000).

For some years there were some quantitative estimates of the unreported catch either from surveys or onboard observers (Table 5.3). Those estimates were used as “anchors” to convert the qualitative categories of incentives to quantitative percentages of the total catch. At least one anchor point is needed for each fishery; however, if more anchors are available, they can be used to double check the interpolated results. I chose anchor points that are more reliable than the others (bold face entries in Table 5.3). Using the anchors, interpolation values were set for the different categories of incentives in such a way that 'medium high' is 80% of the upper bound, 'medium' is 60%, 'low medium' is 40%, and 'low' is 20% (Ainsworth and Pitcher, 2005), see Table (5.4). It is basically a matter of distributing the five categories into five equally spaced ratios, the scaling factor in Table (5.4) i.e., the range for "high" will be 1 – 0.8, medium/high 0.6 – 0.8,…low 0 – 0.2. The bold face entries in Table (5.4) are anchors used for interpolation and the italic entries are interpolated values.

Based on Table (5.4), all the qualitative categories of the unreported catch in Table (5.2) were converted to quantitative values as shown in Table (5.5). The percentage values were converted to absolute values using the reported catch given in Table (5.1). The estimated ranges of unreported catches are given in Table (5.6).

To examine the uncertainty in the estimates of the unreported catch, a Monte Carlo simulation was done. Five thousand samples were taken from asymmetrical triangular distributions with end points being the upper and lower estimates for each value as given in Table (5.6). An asymmetrical triangular distribution was chosen because the likely limits were neither symmetrical nor normally distributed. The extreme values far away from the median were regarded as less likely (Kalikoski *et al.*, in press). The mean and the 95% confidence intervals were calculated.

Table 5.1 Reported catch (mean of 5 years) of three Eritrean fisheries (10^3 t).

Fishery	1950-54	1955-59	1960-64	1965-69	1970-74	1975-79	1980-84	1985-89	1990-94	1995-99	2000-04
Small pelagic	8.00	18.84	6.66	13.94	9.70	0.54	0.16	0.08	0.09	0.04	0.01
Finfish trawl	0	0.01	1.04	1.28	0.82	0.28	0.07	0.20	1.10	2.18	1.59
Shrimp	0.03	0.03	0.02	0.04	0.01	0.03	0.01	0.01	0.01	0.01	0.11

Table 5.2 Qualitative categories of incentives to misreport catch based on the influences from Table (D.1) in the Appendix.

Fishery	1950-54	1955-59	1960-64	1965-69	1970-74	1975-79	1980-84	1985-89	1990-94	1995-99	2000-04
Small pelagic	L	L	LM	M	L	L	LM	LM	L	L	L
Finfish trawl	-	M	H	H	L	L	LM	L	MH	LM	M
Shrimp	L	M	H	H	L	L	LM	L	H	MH	M

Table 5.3 Anchor points as a percentage of total extracted catch (reported plus unreported), bold entries are anchors chosen as references.

Fishery	1950-54	1955-59	1960-64	1965-69	1970-74	1975-79	1980-84	1985-89	1990-94	1995-99	2000-04
Small pelagic				**5**[a]							
Finfish trawl			**90**[b]	30-50[a]			26-40[c]			18 – 40[d]	25 – 32[d]
Shrimp			**90**[b]	**90**[a]			32[c]			60 – 95[d]	20 – 66[d]

[a] Grofit (1971): estimate from onboard observation

[b] Ben-Yami (1964): estimate from onboard observation

[c] Blindheim (1984): from survey data

[d] MOF (1996): estimate from onboard observation

Table 5.4 The interpolated values (in %) of unreported catch for the different qualitative categories. Bold entries are anchors used as references and italic are interpolated values.

Categories	Scaling factor	Small pelagic	Finfish trawl	Shrimp
H	1	*8.33*	**90**	**90**
MH	0.8	*6.67*	*72*	*72*
M	0.6	**5.00**	*54*	*54*
LM	0.4	*3.33*	*36*	*36*
L	0.2	*1.67*	*18*	*18*

Table 5.5 The interpolated ranges of estimates of unreported catch as a percentage of the total extracted catch.

Fishery	1950-54	1955-59	1960-64	1965-69	1970-74	1975-79	1980-84	1985-89	1990-94	1995-99	2000-04
Small pelagic	0 - 1.67	0 - 1.67	1.67 - 3.33	3.33 - 5	0 - 1.67	0 - 1.67	1.67 - 3.33	1.67 - 3.33	0 - 1.67	0 - 1.67	0 - 1.67
Finfish trawl	0	36 - 54	72 - 90	30 - 90	0 - 18	0 - 18	18 - 36	0 - 18	54 - 72	18 - 36	36 - 54
Shrimp	0 – 18	36 - 54	72 - 90	73 - 90	0 - 18	0 - 18	18 - 36	0 - 18	72 - 90	54 - 72	36 - 54

Table 5.6 Estimates of unreported catch (10^3 t). Lower and upper refer to the range of unreported catch estimates.

Fishery		1950-54	1955-59	1960-64	1965-69	1970-74	1975-79	1980-84	1985-89	1990-94	1995-99	2000-04
Small pelagic	lower	0	0	0.11	0.48	0	0	0	0	0	0	0
	upper	0.14	0.32	0.23	0.73	0.16	0.01	0.01	0	0	0	0
Finfish trawl	lower	0	0.01	2.67	0.55	0	0	0.02	0	1.29	0.48	1.25
	upper	0	0.01	9.34	11.52	0.18	0.06	0.04	0.04	2.84	1.23	2.61
Shrimp	lower	0	0.02	0.05	0.11	0	0	0.01	0	0.01	0.01	0.06
	upper	0.01	0.04	0.18	0.36	0.01	0.01	0.02	0.01	0.02	0.03	0.13

5.1 Results and discussion

The estimated overall extractions by the three fisheries from the Eritrean Red Sea are higher than the official report (Figure 5.1). The total extraction (full line in Figure 5.1) is the reported plus the unreported catches. The latter is the mean of 5000 Monte Carlo samples and its 95 % confidence intervals are given by the error bars. The results are averages over the 5 year periods in which the analysis was carried out. The small pelagic fishery has the smallest unreported catch, a maximum of 5% of the total extracted catch. Finfish trawl and shrimp fisheries have a high proportion of unreported catch. When the fishery industry was operating smoothly in the 1950s and 1960s and after 1993, the finfish trawl fishery was underreported by 26 – 84% and the shrimp fishery by 18 – 89%. Adding the three fisheries together (Figure 5.1d), the catch is underreported by 21%. The interpolated quantitative ranges match quite well with those periods where anchor points exist, except in one period, finfish trawl 1965 – 69. For this period, the extreme upper and lower values from the anchor and the interpolated values were taken. Though only one anchor point can be enough to carry out the analysis, having more anchor points helps to double check the results.

All the fisheries show a clear decline in catch in the 1970s and 1980s, mainly due to instability in the region. While finfish trawl and shrimp fisheries revived after the independence of Eritrea in 1993, the small pelagic fishery did not as the fish meal factories and their infrastructure were destroyed. Comparing the three fisheries, the small pelagic is the “cleanest” fishery because it has the smallest unreported catch. As its main end product is fish meal, all the catch is used and nothing is discarded. Also, the beach seine gear, dragged manually in shallow waters, is not so destructive to the ecosystem. It had the least problem of misreporting as well. All the fish meal was exported and there is a good record of the export.

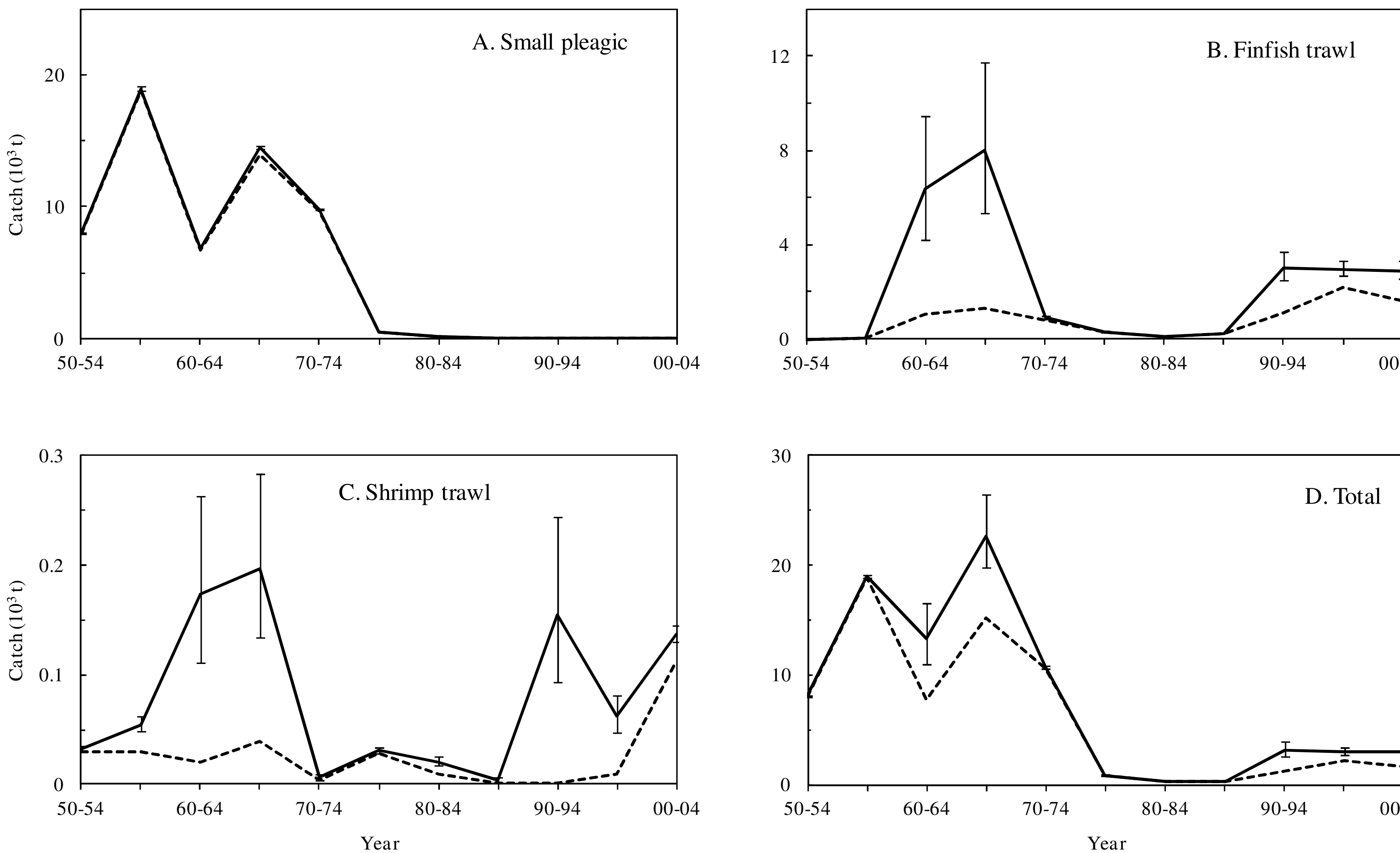


Figure 5.1 Estimated total extractions by three fisheries in the Eritrean Red Sea. The broken line is the reported catch and the full line is the total including the unreported catch. Error bars are the 95% confidence intervals. Note that the scales of the Y-axes are different.

Both finfish and shrimp trawl fisheries have a high level of unreported catch, almost completely from discarding. They both use unselective trawl gear. Once the net is hauled onboard, a large proportion of the catch is thrown back to the sea. These are species which do not have any value in the market or are the small sizes of valuable fishes. The unreported catches of finfish trawl and shrimp fisheries are higher in the 1950s and 1960s than after 1993. This can be attributed three major factors. First, in the 1950s and 1960s, these fisheries were in an experimental stage (Ben-Yami, 1964; Grofit, 1971). Second, the technology used was not as advanced as that used at the present. Third, fishery regulations hardly existed at the time. There was no catch monitoring program, and fisheries were managed by a small division within the port administration of the then Ethiopian government (Ben-Yami, 1964), based in Addis Ababa, far from the coast. On the other hand, after 1993, the fisheries started based on the knowledge accumulated earlier. The technology used is more advanced. The regulation is also better, being managed by a full-fledged ministry, Ministry of Fisheries of the Eritrean government, stationed on the coast. It has regulation mechanisms such as the fishery proclamation of 1998 (MOF, 1998), which aims to regulate fishing activities. It also has monitoring and surveillance programs. For example, trawlers are not allowed to fish in coastal waters shallower than 30 m (Hartmann, 1997). Moreover, an observer is placed in every trawler to monitor the operation and report the retained and discarded catch.

For the shrimp fishery, the catch increased rapidly from the mid 1990s to 2000, however the increase in the unreported catch is less. It could be that the new shrimp grounds found by the industry in the late 1990s have good concentrations of shrimp and low by-catch (Gebremichael *et al.*, 2001). The shrimp fishery has a potential for future expansion. If so, methods of by-catch reduction (Kennelly and Broadhurst, 2002) should be encouraged.

Providing quantitative estimates of unreported catch demands some daring assumptions and they can rightly be criticized. I believe this research will trigger some discussions among researchers and will bring forth feedbacks. There are many subjective opinions in the analysis that need to be reviewed by experts so that the results can be used with more confidence in decision making. However, the procedure is easy to understand and is fully transparent so that values can be adjusted to take account of such comments.

This chapter focuses the method of estimating unreported catch using qualitative data and anchors. It does not examine the composition of the unreported catch. This would be useful especially for discarding, which is done in Chapter 4 (see Figure 4.5 and Table C.7 in the Appendix for composition of trawl discards). The composition of the discards can provide information for management. The life history and behaviour of the discarded species can be used to at least minimize their incidental catch, e.g. mesh size can be regulated based on the maturity size of the discarded species. Eritrea has a policy of increasing effort as the current catch level, based on reported catch, is lower than the estimated potential; however the unreported catch should be considered in calculating the total extraction from the ecosystem and effort increase in the future. In addition, it is highly recommended that the increase in effort to focus on the small pelagic fishery. First, it is a resource with big potential, which has not been used since the fishery revived in 1993. Second, it is a cleaner fishery in terms of discard than the others.

CHAPTER 6: Ecosystem based assessment of the Red Sea fisheries

6.1 Synopsis

An ecosystem-based framework was used to examine the Red Sea ecosystem with emphasis on the fisheries. Ecopath with Ecosim (EwE) modelling tool was used to examine the organisms in the Red Sea, their interactions, including human impacts. Time dynamic simulations were run to quantify the impact of fishery, which is the main direct anthropogenic impact on the ecosystem. The model was fitted to a time series of observed catch and effort to validate its ability to emulate the processes in the ecosystem. Then the model was used to predict the consequences of different fishing scenarios: maintaining the status quo, banning all fishing, and increasing the fishing rate at the average it has been increasing by in the last 10 years. Monte Carlo simulation was used to examine the sensitivity of the predictions to changes in the model input parameters and the risk of the biomasses of the groups falling beyond certain percentages of the starting biomass value of the model were calculated. Equilibrium surplus yield analysis was carried out on the major groups affected by the fishery. Last but not least, the model was used to examine the conflict between artisanal and industrial fisheries in the Red Sea by running scenarios where the fishing effort of each sector was doubled one at a time and the impact on the biomasses of the groups fished by the other sector were calculated.

6.2 Introduction

Quantitative assessment of fisheries has evolved in the last 6 decades from the single species assessment (Beverton and Holt, 1957) to multispecies evaluation and recently into ecosystem-based management, although the latter is still embryonic (Browman, 2000; Pikitch *et al.*, 2004). Each step in this progression addressed certain questions pertinent at the time of their development. This progression is continuing as new knowledge is acquired about ecosystems, including human interactions, and drawbacks of the already existing approaches are identified. The more recent approach, ecosystem-based management (EBM) attempts to put fisheries management into a 'holistic' framework, trying to avoid the pitfalls of reductionism. A lot has been written about EBM, some attempting to define and/or frame it (Link, 2002; Pikitch *et al.*, 2004) to others developing conceptual or software tools for its implementation (Brodziak and Link, 2002; Smith *et al.*, 2007). EBM's acceptance has grown over time and it is under serious consideration by both researchers and practitioners, although poorly implemented as yet (Pitcher *et al.*, 2009). Ecosystem modelling is an important component of EBM, as it enables us to translate the ideas of EBM into workable quantitative assessment tools (Plagányi, 2007). Ecopath with Ecosim (EwE) is one of these tools (Pauly *et al.*, 2000), and it has been used widely, in different ecosystem types. Here, I document the construction and application of an EwE model of the Red Sea, to assess the fisheries in an ecosystem-based framework.

The Red Sea is one of the Large Marine Ecosystems (LME), the large regions of the world oceans, based on its physical parameters, ecology, and exploitation history (Sherman and Alexander, 1986). Although the management of the fisheries is performed by the different countries in their own respective waters, it is helpful to obtain a general ecological understanding of the whole system. Thus, the model incorporates all Red Sea organisms from primary producers to top predators, and human impact through the fisheries.

The habitat and trophic parameters of the organisms are very important for modelling. The following habitat definitions based on FishBase (Froese and Pauly, 2012) are used explicitly in the building the model and to categorize organism by their habitats:
Reef associated: living and/or feeding on or near coral reefs, between 0 – 200 m;

Pelagic: occurring mainly in the water column between 0 and 200 m, not feeding on benthic organisms;

Demersal: living and/or feeding on or near the bottom, between 0 – 200 m;

Benthopelagic: living and/or feeding on or near the bottom, as well as in midwater, between 0 – 200m;

Bathypelagic: Region of the oceanic zone between 1,000 m to 4,000 m; between the mesopelagic layer above and the abyssopelagic layer below. Living or feeding in open waters at depths between 1,000 and 4,000 m. In FishBase this term is used to include the depth range from 200 m to the bottom and thus the zones mesopelagic, bathypelagic and abyssopelagic;

Bathydemersal: living and/or feeding on or near the bottom, below 200m.

These are habitat descriptions in relation to the location of mainly fishes in the ecosystem given in FishBase. However, these are not exhaustive list of habitats. For example, in the model sea grass and sea weed habitats are explicitly included.

6.2.1 The Ecopath model

Ecopath is an ecosystem modelling tool used to account for the energy transfers in an ecosystem (Polovina, 1984; Christensen and Pauly, 1992). Its basic feature is that energy can be transferred from one ecosystem group to another, but the overall transfers are in equilibrium for a period of arbitrary duration. This is in line with the first law of thermodynamics (law of conservation), which states energy can be changed from one form to another, but it cannot be created or destroyed.

The first Ecopath model (Polovina, 1984) was developed to study the ecosystem of the French Frigate shoals, an atoll near the centre of the Northwestern Hawaiian islands. Different scientists were researching and estimating different aspects of the ecosystem and Ecopath was used to put together the estimates in order to get a quantitative picture of the atoll's ecosystem. Ecopath was then applied to a wide range of ecosystems (Christensen and Pauly, 1993). In the early development of Ecopath, its steady-state or equilibrium assumption was understood to mean that the mean annual biomass for each species group does not change from year to year (Polovina, 1984). In the later development of EwE (Christensen and Pauly, 1992), this assumption was replaced by an emphasis on 'mass- balance', implying that there could be change in biomass over time (i.e., biomass accumulation), but the net change over the whole system remains zero.

Ecopath has two master equations. The first one states biological production within a group equals the sum of mortalities by predation and fisheries, net migration, biomass accumulation and other unexplained mortality as expressed in the equation:

$$B_i \cdot \left(\frac{P}{B}\right)_i = Y_i + \sum_{j=1}^{n} B_j \cdot \left(\frac{Q}{B}\right)_j \cdot DC_{ij} + E_i + BA_i + B_i \left(\frac{P}{B}\right)_i \cdot (1 - EE_i)$$

Where B_i and B_j are biomasses of prey (*i*) and predator (*j*), respectively; P/B_i is the production/biomass ratio; Y_i is the total fishery catch rate of group (*i*); Q/B_j is the consumption/biomass ratio; DC_{ij} is the fraction of prey (*i*) in the average diet of predator (*j*); E_i is the net migration rate (emigration – immigration); and BA_i is the biomass accumulation rate for group (*i*). EE_i is the ecotrophic efficiency; the fraction of group mortality explained in the model.

The second equation called the energy equation, states consumption within a group equals the sum of production, respiration and unassimilated food as expressed in the equation:

$$B \cdot \left(\frac{Q}{B}\right) = B \cdot \left(\frac{P}{B}\right) + (1 - GS) \cdot Q - (1 - TM) \cdot P + B \left(\frac{Q}{B}\right) \cdot GS$$

Where GS is the fraction of the food that is not assimilated; and TM is the trophic mode expressing the degree of heterotrophy; 0 and 1 represent autotrophs and heterotrophs, respectively. Intermediate values represent facultative consumers.

Predation mortality is the parameter that connects the different groups in the system. What is predation mortality for the prey is consumption to the predator and Ecopath uses a set of algorithms to simultaneously solve the above linear equations for all the functional groups under the assumption of mass balance. The basic inputs of Ecopath are biomass, production per unit biomass (P/B), consumption per unit biomass (Q/B). Because of the mass-balance assumption, Ecopath can estimate one free parameter of the basic input for each group. Diet composition is also basic input for Ecopath and has to be entered, not estimated by the model.

6.2.2 Ecosim

Ecopath gives a snapshot of the ecosystem at one time. Ecosim, on the other hand, is time dynamic simulation (Walters *et al.*, 1997) and can be used in policy exploration. A mass-balanced Ecopath model is used for Ecosim runs driven by fishing mortality. Change in biomass rates over time and the flux of biomass among the groups is expressed by varying biomasses and harvest rates. Simulation is used to fit the predicted biomass to independent time series data. The model can also be driven by climate or nutrient. It is in Ecosim that the effect of fishing on the ecosystem is addressed. In the policy exploration facility, four policy objectives are included: maximize fisheries rent, social benefits, mandated rebuilding of species and ecosystem structure or 'health' (Christensen *et al.*, 2000). The basic differential equation used in Ecosim is:

$$\frac{dB_i}{dt} = g_i \sum_{j=1}^{n} f\left(B_j, B_i\right) - \sum_{j=1}^{n} f(B_j, B_i) + I_i - (M_i + F_i + e_i) \cdot B_i$$

where dB_i/dt represents biomass change rate of group (i) during the interval dt; g_i represents the net growth efficiency (production/consumption ratio); I_i is the immigration rate; M_i and F_i are natural and fishing mortality rates of group (*i*), respectively; e_i is emigration rate; and $f(B_j,B_i)$ is a function used to predict consumption rates of predator (*j*) on prey (*i*) according to the assumptions of foraging arena theory (Walters and Martell, 2004; Walters and Christensen, 2007). It is modified by the predator-prey vulnerability parameter assigned to the interaction.

Besides a snapshot of the ecosystem (Ecopath) and time dynamics (Ecosim), the EwE package also has a dynamic spatial simulation called Ecospace (Walters *et al.*, 1999). It remedies the assumption of homogenous spatial behavior of organisms which is implicit in Ecopath and Ecosim. The use of Ecospace so far has been mainly in placement and evaluation of marine protected areas (MPA) (Walters, 2000; Varkey *et al.*, 2012). Ecotracer is another component of EwE which deals with the movement and accumulation of contaminants and tracers in the food web (Christensen and Walters, 2004). For further accounts of EwE, notably for the theoretical and mathematical backgrounds see (Walters *et al.*, 1997; Christensen *et al.*, 2008). Plagányi and Butterworth (2004) and Plagányi (2007) present critical reviews of the EwE approach.

The main objective of this chapter is to assess the Red Sea fisheries in ecosystem based framework. This was accomplished by building an ecosystem model of the Red Sea which:

- Presents a quantitative description of the structure of the ecosystem in terms of the 'players' (groups), which include the organisms living in that sea and the fisheries, and their interactions, i.e., the flux of energy from one group to another, and including basic ecosystem parameters for each group in the model;
- Quantifies and evaluates the effect of fisheries on the system;
- Explores the interaction between the different fisheries, and their policy implications. The specific question addressed is whether the industrial and artisanal fisheries have negative impact on each other (the assumption that they do has been a frequent cause of conflict).

6.3 Materials and methods

6.3.1 Ecopath

Defining the boundaries of an ecosystem to be modeled can be difficult, especially in marine systems where the boundary can be elusive, and varies through time. However, this is not a problem here, as the whole Red Sea is taken into consideration. The fact that the Red Sea is an enclosed sea with little exchange with neighboring ecosystems makes it ideal to be modeled as a unit.

The data needed to build an Ecopath model is extensive. The Red Sea organisms included in the model are divided into two categories, fish and non-fish, for the convenience of data source and calculating parameters.

6.3.1.1 Fish species

The Red Sea, a subtropical system, has high diversity. There are more than 1290 fish species reported for the Red Sea (Froese and Pauly, 2012), the list of fish species is given in the Appendix (Table E.1). It is neither practical nor necessary for each species to be represented as a group by itself in the model. Grouping of similar species is possible and necessary. Here, grouping was done using parameters that define the trophic interaction of the organisms: habitat, trophic level and size. Using these parameters the fish species were grouped into 20 ecologically meaningful functional groups (Table E.2 in the Appendix). The fish species that are major contributors to the catch of the different major gears in the Red Sea (see Figures 4.4 and 4.5 of Chapter 4) were kept in separate groups, so that detailed analysis on these groups could be carried out.

The two important Ecopath input parameters, consumption rate and production rate for the fish, were calculated using population parameters from FishBase. First priority was given to data from the Red Sea, but when data from the Red Sea could not be found, data were taken from similar ecosystems, i.e., coral reef ecosystems with similar mean annual temperature.

Consumption

The food consumption per unit biomass (Q/B) values for the fish species were taken from FishBase, preferably from the Red Sea. When the Q/B value was not given, the empirical equation developed by Palomares and Pauly (1998) was used:

$$\frac{Q}{B} = 7.964 \cdot 0.204 \log W_{\infty} + 1.965\, T + 0.083A + 0.532h + 0.398d$$

where W_{∞} is asymptotic weight of the species, T is mean annual temperature of the Red Sea, 27.71°C, expressed as 1000/(T°C+273.1), A is the aspect ratio obtained from FishBase, h and d refer to the types of food consumed (i.e., for herbivores h=1, d=0; for carnivores h=0, d=0; for detritivores d=1, h=0).

When W_{∞} was not directly given it was calculated from length-weight relationship:

$$W_{\infty} = a \cdot {L_{\infty}}^{b}$$

where L_{∞} is the asymptotic length, and *a* and *b* are constants from FishBase.

When the aspect ratio was not available, a different empirical equation developed by Pauly (1986) was used to calculate the consumption per unit biomass (Q/B):

$$\frac{Q}{B} = 10^{6.37} \cdot 0.0313^{(\frac{1000}{T})} \cdot {W_{\infty}}^{-0.168} \cdot 1.38^{Pf} \cdot 1.89^{Hd}$$

where T is the Red Sea mean annual temperature in degree Celsius (27.71°C), Pf is feeding mode parameter set to 1 for predators and zooplankton feeders, and Zero for other fish species, Hd is diet composition parameter set to 1 for herbivores and zero for omnivores and carnivores.

Production

The production per unit biomass (P/B) is equal to the total mortality, which is the sum of natural mortality and fishing mortality (Z = M + F). For species not exploited P/B equals M. For all the species M value was searched in FishBase and when it was not available the empirical formal of Pauly (1980) was used.

$$M = K^{0.65} \cdot L_{\infty}{}^{-0.279} \cdot T^{0.463}$$

Where K is the von Bertalanffy growth constant and L∞ is the asymptotic length both obtained from FishBase and T is Red Sea mean annual temperature (27.71^{o}C).

Biomass

Detailed biomass data was not available for all the fish species included in the model. However, extensive search resulted in some data, which were used as a starting point to parameterize the model. For pelagic fishes an acoustic survey in the southern Red Sea (Massé and Araia, 1997), for demersal fish a trawl survey (Blindheim, 1984), for coral reef fish visual censuses (Roberts and Ormond, 1987; Bouchon-Navaro and Bouchon, 1989; Zekaria, 2003) were used. Abundance values of a wider range of organisms were also available (Antoine *et al.*, 1997; Price *et al.*, 1998; Tsehaye, 2007).

6.3.1.2 Non-fish groups

The non fish groups are diverse with different taxonomic composition. They include marine mammals, turtles, birds, invertebrates and primary producers. Shrimp is the most important of the non-fish groups for fisheries. Hence, it is given its own functional group, as the main focus of the model is ecosystem-based assessment of fisheries in the Red Sea. Data of non-fish groups were searched for the Red Sea; in additional, data from similar ecosystems were also used. For invertebrates, SeaLifeBase (Palomares and Pauly, 2012) and benthic invertebrate population dynamics database (Brey, 2001) were used as sources. The list of the non-fish groups together with their parameters and sources is given in the Appendix (E.1.1).

6.3.1.3 Diet matrix

Diet data for the fish species, unless specified otherwise, was obtained from FishBase. Priority was given for data from the Red Sea, but when not available, data from similar ecosystems were used. For the non-fish group, diet compositions were compiled based on similar coral reef ecosystem models of the Eritrean Red Sea (Tsehaye, 2007), Caribbean (Opitz, 1996; Arias-González, 1998), Indonesia (Buchary, 1999; Ainsworth *et al.*, 2007), and French Frigate Shoals-Hawaii (Polovina, 1984). The diet matrix table is given in the Appendix (Table E.4)

6.3.1.4 Fishery

The fishery data for the model were taken from the data compiled for the catch reconstruction of Red Sea fisheries, as presented in Chapter (4). These fisheries can be divided into two main categories: artisanal and industrial. The major fishing gears from each group are represented in the model. For the artisanal sector the major gears are handlines, gillnets and beach seines; while the major industrial fishing methods are bottom trawling and purse seining. As the main objective of the model is to explore the Red Sea fisheries at the ecosystem level, the species which contribute the highest proportion to the catch of the various fishing gears were assigned to distinct functional groups in the model (for each gear). Their names in the model are the gear name followed by 'fishes' e.g., fishes targeted by handlining are called 'handlining fishes'. The major taxonomic groups for each gear that are given a separate functional group in the model accounted for more than 80% of the catch by respective gears (see Figure 4.4 for artisanal and Figure 4.5 for industrial gears in Chapter 4, and Appendices C.2 - C8). The minor portions were divided among other functional groups by matching the catch compositions to the functional groups. The shark catch was similarly divided between handlining and gillnet, as both gears are used to catch sharks in the Red Sea. Discard from the trawl fishery was included in the model, and was made to flow to detritus. The total catch values were expressed per unit area ($t \cdot km^{-2} \cdot year^{-1}$). The five fisheries are named by their respective gears: handline, gillnet, beach seine, trawl and purse seine; while the functional groups in the model which are their target are: handline fishes, gillnet fishes, beach seine fishes, shark, trawl fishes, purse seine fishes and shrimp. Sharks are targeted by both handline and gillnet, while shrimps are targeted by trawl; however, because of their importance for the fisheries they are given separate groups. So in the following part when 'shrimp' is mentioned, it is the trawl fishery, but the shrimp catch is analyzed separately from the fishes caught by trawling.

6.3.1.5 Parameterizing / balancing the model

Parameterizing a model is making sure the mass balance equations for each group are fulfilled simultaneously. The model was parameterized following the procedure outlined in the Ecopath with Ecosim manual (Christensen *et al.*, 2008), i.e., the input that were less reliable or whose value had been assumed were changed progressively, and the model was run to check the progress of balancing. The diet matrix, being the most uncertain, was the input that was adjusted the most during balancing the model, while P/B and Q/B were changed less, if at all. Model balancing was terminated when it fulfilled the requirements of balanced models: all EE less than 1, the gross food conversion efficiency (GE, i.e., production/consumption) with the range of 0.1 – 0.3 for fish, and all respiration/biomass ratios within a physiologically reasonable range.

6.3.2 Ecosim

Unlike Ecopath, which is static, Ecosim is a time dynamic simulation. The latter was the fitted to time series data. This enabled verifying the parameterization of the Ecopath model, and after some adjustments, to performing an equilibrium analysis with Ecopath, and an exploration of fishery policy scenarios with Ecosim.

6.3.2.1 Fitting to time series data

A time series simulation was made to fit the model predictions to independently calculated catch time series. This fitting exercise helps to validate the ability of the model to mimic the actual process in the ecosystem, including its fishery. A time series of fishing effort was needed for this exercise. The procedures and the results of the fishing effort reconstruction for the artisanal fisheries are given in the Appendix (E.2.1), while effort data for industrial.were kindly extracted by Dr. Reg Watson from the database compiled in support of the publication by Anticamara *et al.,* (2011).

In order to test the ability of the model (which pertains to 2006) to mimic the functioning of the Red Sea ecosystem, e.g. to predict the catch data from 1950 – 2006, it was made to run from 1930 – 2006, i.e., first to let the model mimic the situation before 1950 (with restored biomass of the predators that have been depleted by the fishery), so that it will be ready for the procedure of fitting to the independent data (Cox *et al.*, 2002; Villy Christensen pers. comm.). The procedure consists of first scaling the time series of effort between 0 and 1, and taking the effort of 2006 to be 1. Then, the relative effort of 1950 is carried backward for few years (20-30 years, i.e, starting 1920 or 1930), and the simulations was run in Ecosim, until they stabilize in 1950. Because the simulation stabilized when it was run from 1930, the simulation from 1920 was discarded and all simulations were done from 1930 – 2006. However, the time series fitting was done only from 1950 – 2006. The fishing effort levels of 1950 were very small compared to 2006, except for the beach seine fishery (Table E.7 in the Appendix), which was a strong vibrant fishery in the 1950s, especially in Eritrea. Later, this fishery was largely abandoned. Thus, for the effort ratio of beach seine, instead of the high value of 1950, an arbitrary low ratio of 0.02 was used for the period from 1930 to 1950. The small effort values for all the fisheries from 1930 – 1950 allowed the model to assume an equilibrium characterized by high biomasses of top predators by the time the actual simulation started in 1950. This is a reasonable assumption that the biomasses of top predators were higher in 1950 before they were fished out in the following decades. More importantly, those values were to be used only as a starting point for the time series fitting, which works by minimizing the sum of squares of the differences between the observed catch and CPUE data and the ones predicted by the model.

During the time series fitting, some of the basic Ecopath input parameters (biomass, P/B. Q/B and diet composition) were modified and the fit rechecked. This procedure was repeated iteratively, and the model fine tuned (particularly the diet compositions, and secondarily the P/B ratios) until the best fit was achieved. Catch per unit effort (CPUE) was used as proxy for biomass to guide the time series fitting. Note that the emphasis of the fitting was not on CPUE, but on the catch time series data, which appear more reliable, given the catch reconstruction documented in Chapter 4.

Trophic flow parameter

A key parameter to be adjusted during time series fitting is vulnerability, a parameter that regulates the flow between different trophic level groups or foraging arena parameter (Walters and Martell, 2004; Walters and Christensen, 2007). Vulnerability depicts the effect of the biomasses of prey and predator on the predation mortality. The minimum value used is 1 when an increase in the biomass of predator does not cause noticeable change in predation mortality, a situation known as prey or bottom-up control. The other extreme occurs when an increase in biomass of predator produces noticeable change in predation mortality known as predator or top-down control. Here, the parameterization of the vulnerability values for the Red Sea was done using both the automated vulnerability search routine in EwE and manually. The vulnerability search routine is an iterative procedure to identify predator-prey interactions that are critical for the model (and presumably the ecosystem) to function. It uses a least-square method to optimize those critical vulnerabilities in order to recreate the observed time series of catch and CPUE. The search begins with all the interactions in the diet matrix, but then later it is focused on the few that are highly influential. Another parameter which affects the feeding behavior of the animals and was adjusted during the fitting process was 'feeding time factor'. It is a measure of how fast organisms adjust their feeding behavior (i.e., their feeding times) so as to stabilize consumption rate per biomass. It ranges between 0, causing feeding time and hence time exposed to predation risk to remain constant, to 1, causing fast time response, which reduces vulnerability to predation (Christensen *et al.*, 2008).

6.3.2.2 Model stability and uncertainty analysis

I tested the stability of the model by subjecting it to three scenarios and running the corresponding three simulations: (i) maintaining the baseline fishing rates, (ii) assuming zero fishing rates for all the gears, and (iii) increasing the fishing rates of each gear by 5% each year, which is the overall increase of the fishing rates in the last 10 years (Table E.7 in the Appendix).

The stability test showed the model's behavior under varying functional group parameters and fishing pressure. If the model behaves in a realistic fashion, then it can be used for fishing policy exploration; otherwise, if unstable results are produced by the model, its use for policy development will not be warranted.

Under the three scenarios, the sensitivity of the model to changes in the basic input parameters was explored using Monte Carlo simulations. The biomasses of all the functional groups were allowed to vary +/- 20% of their original Ecopath values, while P/Q, Q/B and EE were varied +/- 10%, then 100 Monte Carlo draws were made from a uniform distribution. The mean and the standard deviation (SD) were calculated for each simulation to establish a range of error for predictions. In addition, the depletion risk of the fishery groups in a population was explored through a viability analysis, i.e., an estimation of the probability that the biomass can drop below a certain ratio of the original biomass.

6.3.2.3 Equilibrium analysis

Once the model's stability was established and uncertainty analyses were performed, equilibrium analysis was carried out, which provides both important diagnostics and analytical results. The pertinent routine calculates the biomass and catch of the functional groups at different fishing mortality rates. EwE allows this analysis either by taking one group at a time and keeping all the other groups constant (which is thus similar to traditional single species stock assessment; or allowing interaction between groups (which is similar to multi-species stock assessment). For the Red Sea model, the latter was used.

6.3.2.4 Fishing policy exploration

Besides the three scenarios mentioned above, two additional scenarios were run using Ecosim simulations to explore the interaction between the artisanal and industrial fisheries in the Red Sea. This is very important for the region as conflicts between the two fisheries types are common, which has serious impact on the decision-making process. The two scenarios involved are one where the fishing effort of the industrial sector was doubled without changing the artisanal effort, and a second scenario where this was reversed. The simulations were run to predict the biomasses of all the groups until 2030.

6.4 Results

6.4.1 Ecopath

EwE is an ecosystem modelling tool with a wide suite of routines which allows numerous analyses once it is balanced and validated. Here, the general structure of the Red Sea ecosystem model is presented, as are a number of analyses relevant to the main objective of building the model, which is an ecosystem-based assessment of the Red Sea fisheries. The key result of the Ecopath modelling part is a snapshot of the ecosystem with all the basic parameters satisfying all features as outlined above, i.e., all the ecotrophic efficiencies (EE) are less than 1, respiration values are positive (Christensen *et al.*, 2008). This balanced model of the Red Sea (Table 6.1) was used to explore the Red Sea ecosystem using the diagnostic tools provided in EwE.

The food web with all the flows of energy among different groups placed on the order of the trophic level of the groups is given in Figure (6.1). Since the main objective of the model is to explore the fishing activities, the names if the groups which are the prime targets for fishery are colored red. The size of the squares is proportional to the biomass of the groups. Of all the living groups, the primary producers (phytoplankton, sea grass and algae) have biomasses that are notably larger than all other groups. This is summarized in the food web pyramids both for the biomasses and flows (Figure 6.2). The flow pyramid shows flow by trophic level, the bottom plane is the first order consumers and the volume of the compartments is proportional to the sum of all flows at the level or throughput. When drawn to the same scale, pyramids are useful to compare different systems, especially since the top angle of the flow pyramid is inversely proportional to the mean trophic transfer efficiency at trophic level II-IV (Christensen *et al.*, 2008). The Red Sea model is compared with some tropical ecosystem models built using EwE and whose files were available in the Ecopath website (www.ecopath.org; Table 6.2). In terms of fisheries, it is worth noting that the Red Sea has a very low total catch in relation to total biomass (excluding detritus), indicating a lower exploitation.

Table 6.1 The basic parameters of the balanced Red Sea model.

Group No.	Group name	Trophic level	Biomass ($t \cdot km^{-2}$)	P/B ($year^{-1}$)	Q/B ($year^{-1}$)	EE	GE
1	Cetaceans	3.84	0.0610	0.044	5.914	0.025	0.007
2	Dungongs	2.00	0.0029	0.025	11.000	0.000	0.002
3	Birds	4.04	0.0068	0.380	20.000	0.026	0.019
4	Turtles	2.69	0.0555	0.150	3.500	0.137	0.043
5	Trawler fishes	3.38	0.0402	2.680	11.380	0.972	0.236
6	Purse seine fishes	3.53	0.0210	3.085	14.150	0.945	0.218
7	Beach seine fishes	3.09	0.1080	3.250	15.000	0.800	0.217
8	Handlining fishes	3.54	0.0700	1.300	7.887	0.688	0.165
9	Gillnet fishes	4.07	0.0265	2.000	8.000	0.950	0.250
10	Whale shark	3.28	0.0038	0.035	4.000	0.500	0.009
11	Sharks	4.16	0.0076	0.750	4.371	0.950	0.172
12	Rays	2.88	0.0040	0.373	3.000	0.400	0.124
13	Reef top predators	3.76	0.0197	1.052	4.000	0.950	0.263
14	Large reef carnivores	3.51	0.1100	1.240	5.500	0.344	0.225
15	Medium reef carnivores	3.43	0.1380	1.728	7.324	0.576	0.236
16	Small reef carnivores	3.21	0.3800	2.800	10.000	0.636	0.280
17	Reef omnivores	2.88	0.2630	2.700	13.890	0.950	0.194
18	Reef herbivores	2.00	0.2880	3.200	16.000	0.950	0.200
19	Large pelagic carnivores	3.82	0.1050	0.722	6.508	0.960	0.111
20	Small pelagic carnivores	3.44	0.2740	3.162	10.000	0.950	0.316
21	Pelagic omnivores	2.64	0.2660	2.828	10.000	0.950	0.283
22	Demersal top predators	3.58	0.0073	1.300	6.000	0.946	0.217
23	Large demersal carnivores	3.31	0.0160	1.500	7.000	0.439	0.214
24	Medium demersal carnivores	3.04	0.0620	1.990	8.000	0.920	0.249
25	Small demersal carnivores	2.96	0.2230	3.189	12.000	0.960	0.266
26	Demersal omnivores	2.16	0.2960	3.200	14.000	0.940	0.229
27	Demersal herbivores	2.00	0.3600	3.500	16.500	0.975	0.212
28	Benthopelagic fish	2.78	0.2350	1.800	6.000	0.970	0.300
29	Bathypelagic fish	3.11	0.0020	1.749	12.720	0.126	0.138
30	Bathydemersal fish	2.91	0.0040	1.260	6.940	0.831	0.182
31	Shrimp	2.09	0.0100	9.000	25.000	0.609	0.360
32	Cephalopods	2.92	0.3990	3.500	12.000	0.549	0.292
33	Echrnoderms	2.10	0.5960	2.500	8.000	0.553	0.313
34	Crustaceans	2.19	0.8160	6.667	20.000	0.451	0.333
35	Molluscs	2.05	0.3680	9.000	30.000	0.556	0.300
36	Meiobenthos	2.07	0.2950	26.000	100.000	0.402	0.260
37	Corals	2.28	0.9280	2.800	9.000	0.527	0.311
38	Other sessile fauna	2.28	0.8500	3.200	12.000	0.368	0.267
39	Zooplankton	2.11	14.0000	52.000	178.000	0.363	0.292
40	Phytoplankton	1.00	21.5000	110.000	-	0.955	-
41	Sea grass	1.00	11.0000	9.000	-	0.015	-
42	Algae	1.00	38.0000	14.000	-	0.027	-
43	Detritus	1.00	80.0000	-	-	0.034	-

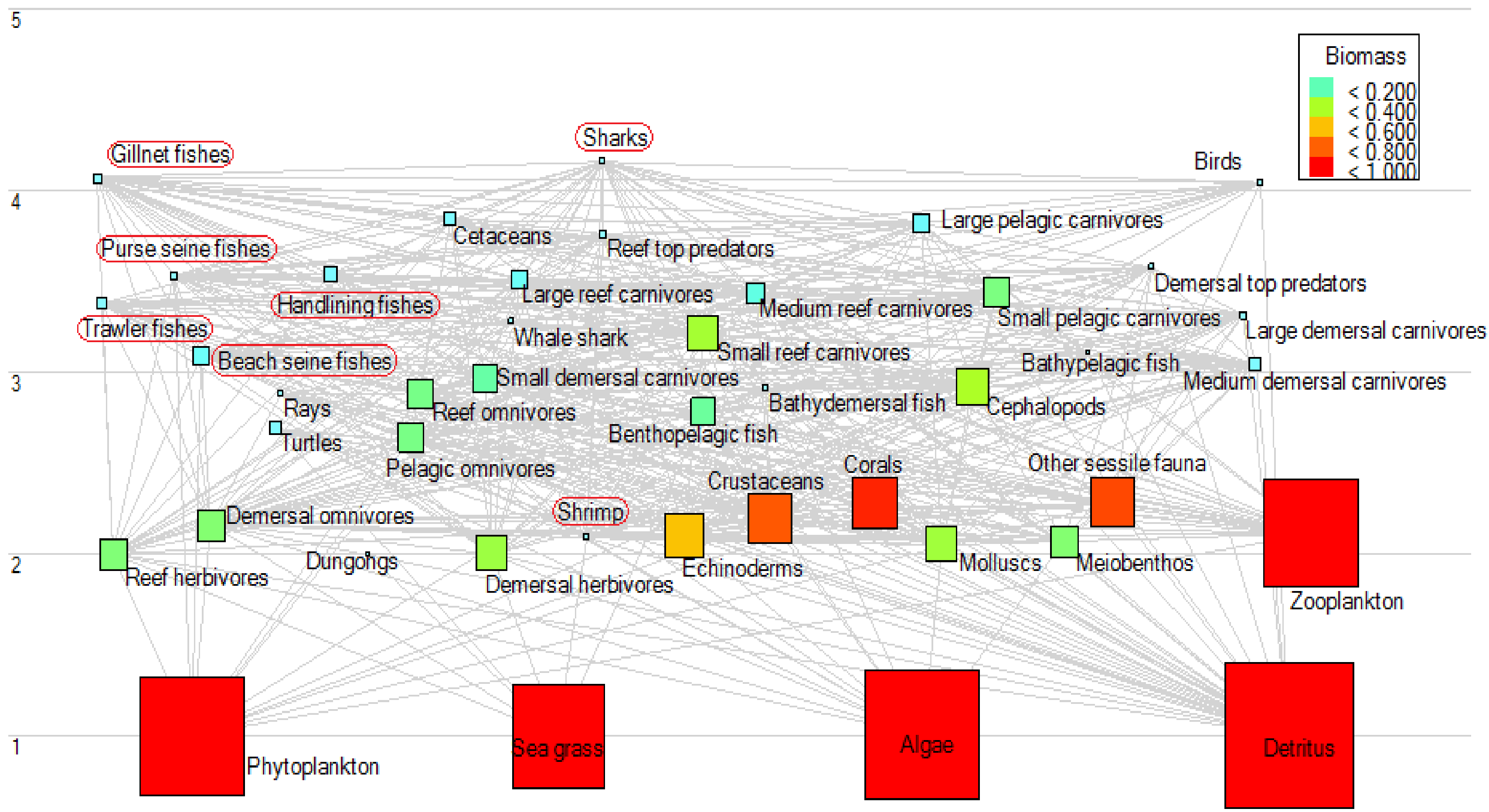


Figure 6.1 Flow diagram of the food web of the Red Sea ecosystem. Rectangles represent the biomass of the functional groups. The names of the major fishing groups are colored red. The numbers on the left are trophic levels.

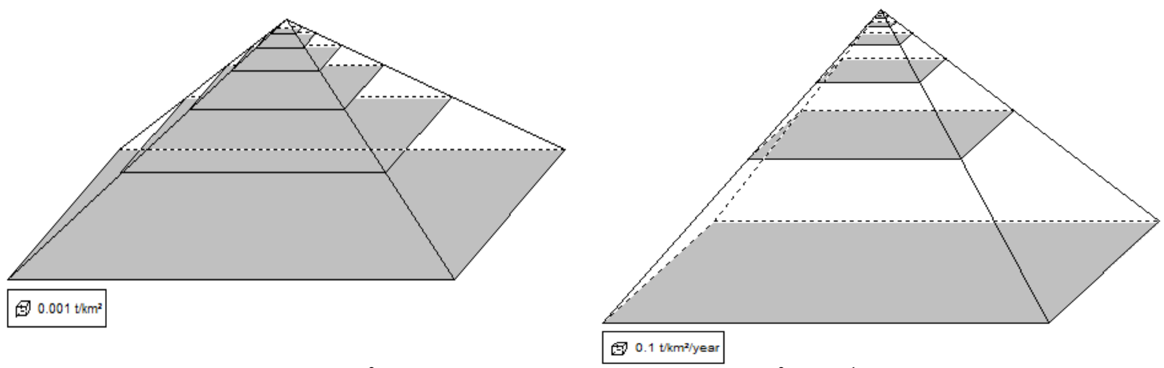


Figure 6.2 Biomass (left, in t·km^{-2}) and flow pyramids (right, in t·km^{-2}·year^{-1}) for the Red Sea model.

The data requirement for an EwE model is huge, and models can be categorized by the quality of the data used for constructing them. This is done using pedigree analysis. It is a routine in EwE which allocates the likely uncertainty associated with input parameters based on pre-defined categories according to the sources of the inputs. Parameters from quantitative research in the model area receive a higher pedigree index, which also means low uncertainty value. On the other hand, parameters estimated by Ecopath receive a lower pedigree index and a higher uncertainty value. Once the indices are assigned for all input parameters, then the routine calculates an overall average ranging between 0 and 1 (inclusive); 1 being model built from local data with high precision (Christensen *et al.*, 2005). There does not exist a single Ecopath model with a pedigree value of 1 (Morissette, 2007). The Red Sea model scored 0.433, while analysis of 50 other models with average of 27 groups resulted in a mean pedigree of 0.44 (Morissette, 2007). Table (6.2) gives the pedigrees of four other tropical ecosystem models compared with that of the Red Sea model. The mixed trophic impact, MTI, (Figure 6.3) shows the combined direct and indirect trophic impacts that a small change in the biomass of one group could have on other groups. If we zoom in only on the fishery groups, the main impacts of the fisheries are, as one would expect, on the group they target (Figure 6.4) but not on the other fishery groups.

Table 6.2 Comparison of the Red Sea model with other tropical ecosystem models using system summary statistics.

Criteria	Red Sea	Great Barrier Reef	Laguna Bay, Philippines	San Miguel Bay, Philippines	West Florida shelf USA
Total boxes	43.00	32.00	17.00	16.00	59.00
Living groups	42.00	30.00	16.00	15.00	55.00
Pedigree index	0.433	0.139	0.499	0.286	0.630
Sum of all consumption (t/km²/year)	2615.82	4314.13	7793.81	769.38	18501.20
Sum of all exports (t/km²/year)	1665.10	1119.89	5901.51	516.19	903.44
Sum of all respiratory flows (t/km²/year)	1330.97	1732.15	3137.23	381.56	5977.33
Sum of all flows into detritus (t/km²/year)	1723.53	4038.89	6544.32	931.41	17273.88
Total system throughput (t/km²/year)	7335.00	11205.00	23377.00	2599.00	42656.00
Sum of all production (t/km²/year)	3756.00	3920.00	10838.00	1080.00	14071.00
Mean trophic level of the catch	3.40	2.49	2.08	3.00	3.51
Gross efficiency (catch/net p.p.)	0.000085	0.002971	0.031380	0.016502	0.000051
Calculated total net primary production (t/km²/year)	2996.00	2846.24	8950.30	897.75	6986.95
Total primary production/total respiration	2.25	1.64	2.85	2.35	1.17
Net system production (t/km²/year)	1665.03	1114.09	5813.06	516.19	1009.62
Total primary production/total biomass	32.49	9.82	49.99	28.65	9.74
Total biomass/total throughput	0.01	0.03	0.01	0.01	0.02
Total biomass, excluding detritus (t/km²)	92.22	289.87	179.05	31.34	717.61
Total catches (t/km²/year)	0.25	8.46	280.86	14.82	0.36
Connectance Index	0.31	0.28	0.21	0.34	0.23
System Omnivory Index	0.24	0.23	0.14	0.17	0.26
Total market value (US$)	234.88	1.20	-	-	0.28
Total value (US$)	234.88	1.20	-	-	0.28
Total variable cost (US$)	187.90	0.61	-	-	0.00
Total cost (US$)	187.90	0.61	-	-	0.00
Profit (US$)	46.97	0.59	-	-	0.28

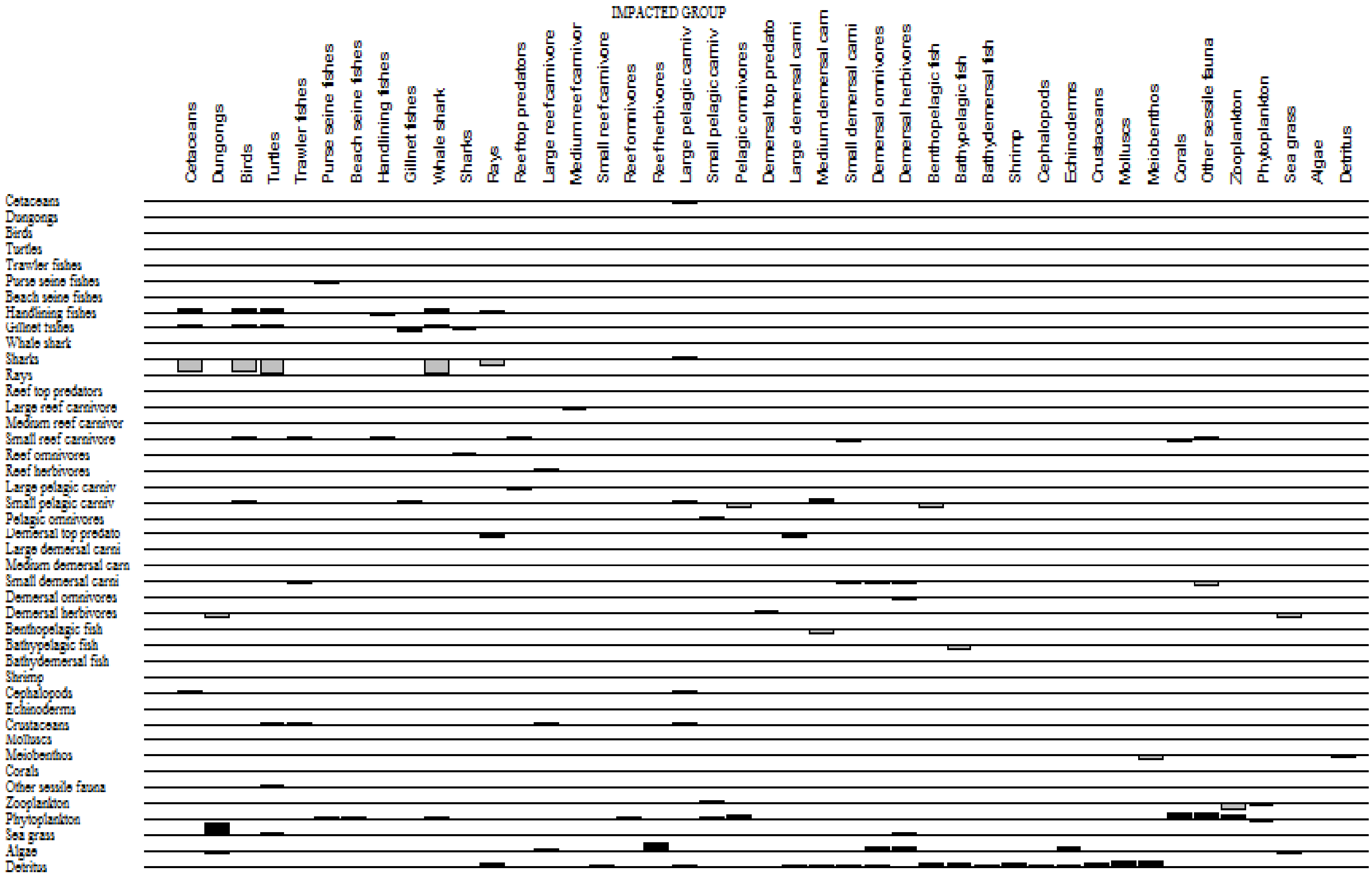


Figure 6.3 Mixed trophic impact (MTI) of the functional groups in the Red Sea model. The upward dark bars and downward lighter bars show the positive and negative impact, respectively, that a small increase of the biomass of an impacting group (Y-axis) would have on all other groups (X-axis).

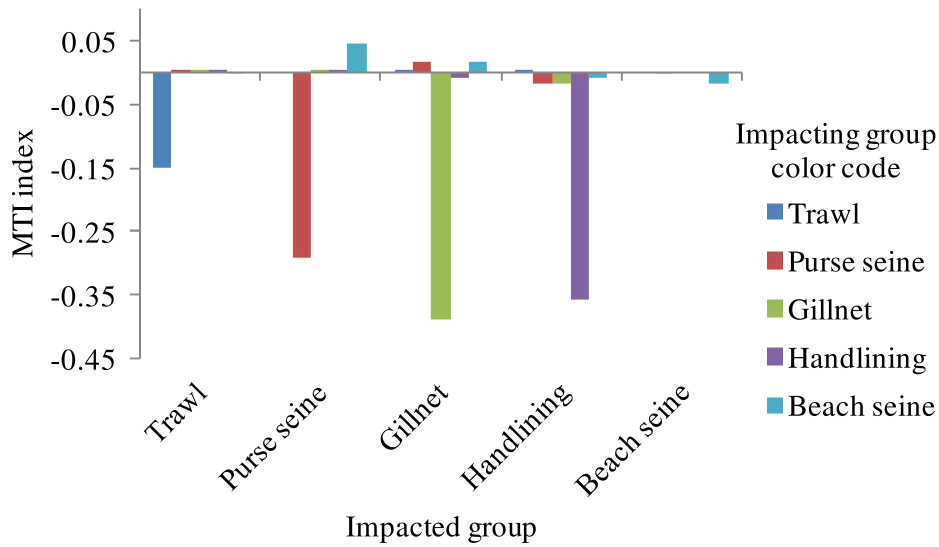


Figure 6.4 Mixed trophic impact of the fisheries of the Red Sea. The gears in the x axis are the impacted groups, while the colours in each cluster are the impacting group.

6.1.1 Ecosim

6.1.1.1 Fitting to time series

After fine tuning the basic Ecopath input parameters, searching for vulnerability values and fitting the time factor, the best fit between the observed and predicted catch was obtained (Figure 6.5). The pattern for the two sets of data was similar for almost all the fisheries. However, a clear distinction is observed between the artisanal and industrial fisheries. The fit is generally better for the industrial fisheries (purse seine, trawl and shrimp). The best fits are for trawl (fishes) and shrimp. For the groups in the artisanal fishery (gillnet, handlining, shark and beach seine fishes), the fits were poor at the beginning of the fitting run. The model was responding to changes in CPUE, which was used as measure of biomass. The CPUE calculated for the artisanal can be divided into two periods, before and after motorization, which started in the 1960s but got its momentum in the 1970s. The expansion of the fishing effort was higher after motorization, and that CPUE calculated after motorization show better representation for the whole Red Sea, the area considered in the model. So, more emphasis was given to the fitting after 1970 and the model predicted the pattern.

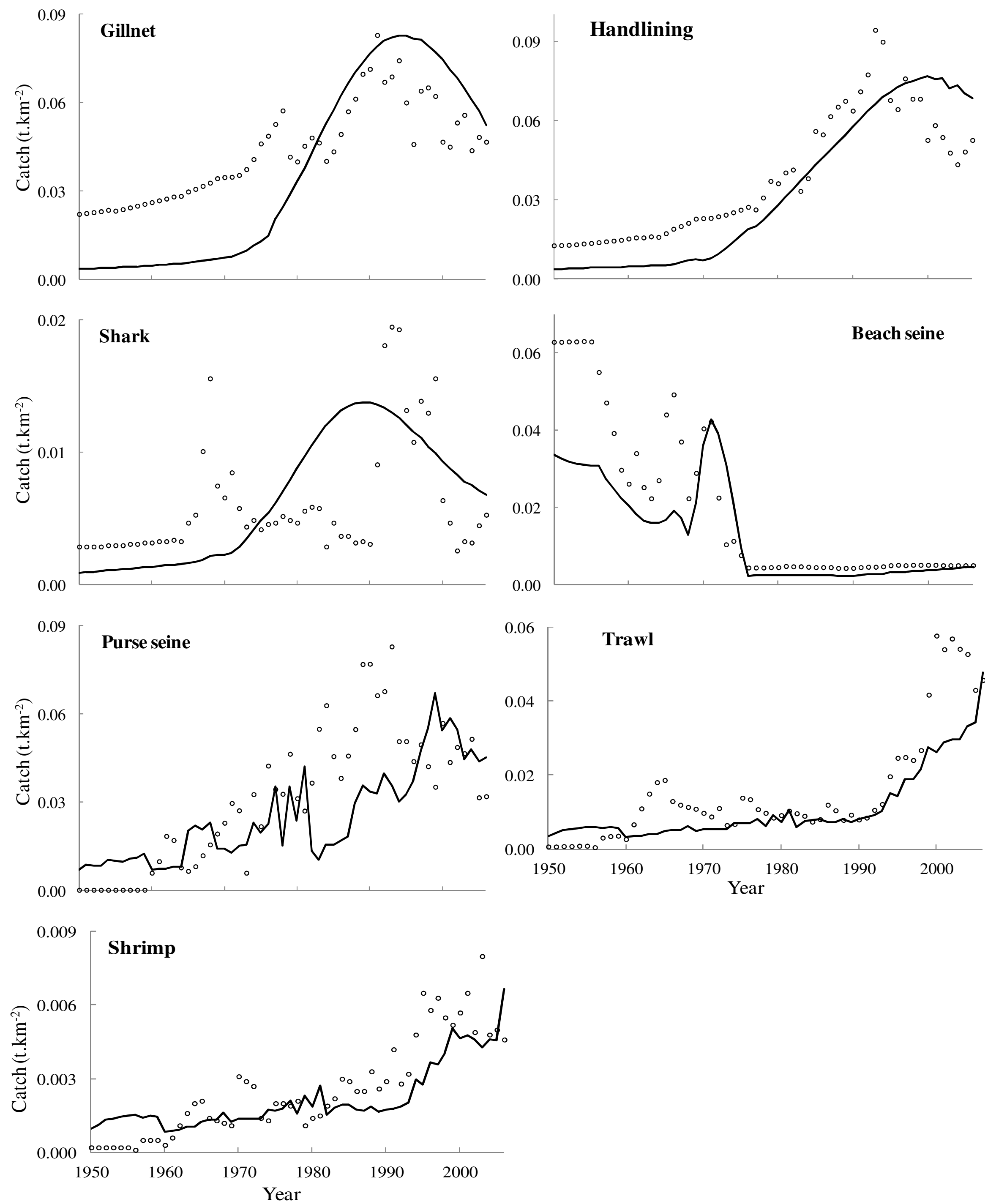


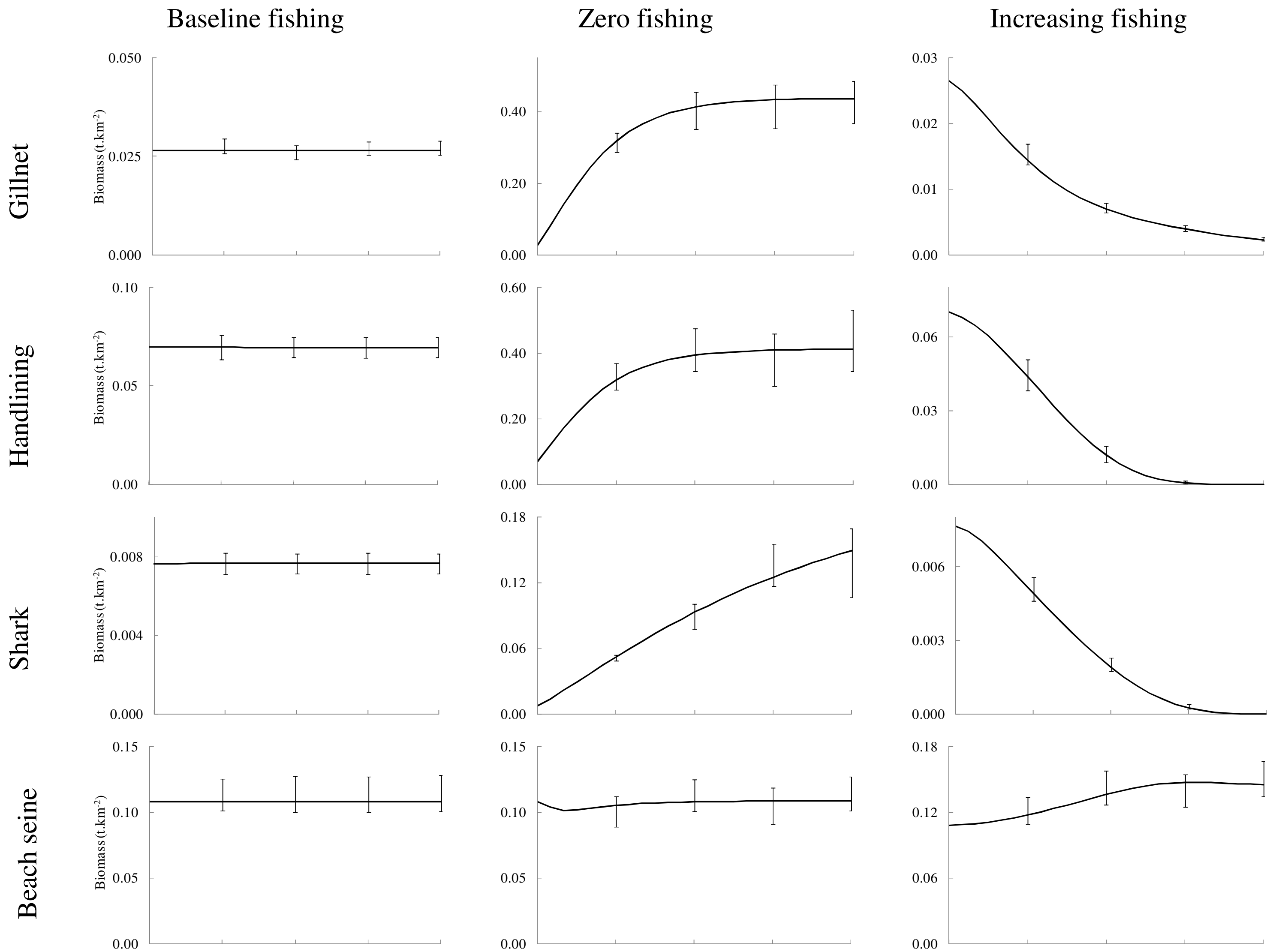
Figure 6.5 Times series of observed catch data from the Red Sea (dots) and catch predicted by the fitted Red Sea EwE model (line) from 1950 – 2006 for the functional groups important in fisheries. The model was driven by independently estimated fishing effort data.

For the vulnerability search routine, the most important functional groups were sharks, gillnet fishes, i.e., the major species targeted by gillnet fishery, and handlining fishes. Changes in these three groups, which are on top part of the food web (Figure 6.1), had a high impact on the foraging arena dynamics of the model. Once the vulnerability values for the three groups were adjusted, the minor groups were easily accommodated, along with the feeding time factor. For all the groups, important in fisheries the latter value was adjusted to zero, which means that the feeding time and hence the time they were exposed to predation risk remained constant. The final vulnerability and the feeding time factor values are given in the Appendix (Tables E.8 and E.9).

6.1.1.2 Stability and uncertainty

Three scenarios run to test the stability of the model generated largely predicable results. When the fishing mortality was kept at the baseline, the biomasses of all the fishery important groups remained more or less constant. When the fishing mortality was set to zero, the biomasses of all the groups increased, except for the fish exploited by beach seines, which decreased slightly at first, then stabilized at a slightly higher level, and the biomass of fish exploited by trawlers, which increased drastically at first, then stabilized at a lower level (but still higher than the initial level). In the third scenario, when the fishing mortality was increased by 5% per year, the biomass of all groups decreased except those exploited by beach seines, which consist of low trophic level fishes. Thus, once the biomasses of predators are decreased, the biomasses these fishes increased, due to reduced predation. The Monte Carlo uncertainty analysis showed all the estimated values were within +/- 1 standard deviation (Figure 6.6).

The depletion risk of the fishery groups in a population viability analysis, i.e., the probability the biomass falling below a certain fraction of the original biomass. For the zero and baseline fishing scenarios did not cause any depletion beyond 50% of the baseline biomass. On the other hand, in the scenario where fishing was increased 5% per year, the probability of the biomass in 2030 dropping below 5% of the baseline was 100% for purse seine, handlining and sharks. Beach seine fishes would not go below 50% of the baseline, while trawler, gillnet fishes and shrimps exhibited varying degrees of depletion (Table 6.3).



Baseline fishing
Zero fishing
Increasing fishing
Gillnet
Handlining
Shark
Beach seine
Biomass (t.km-2)

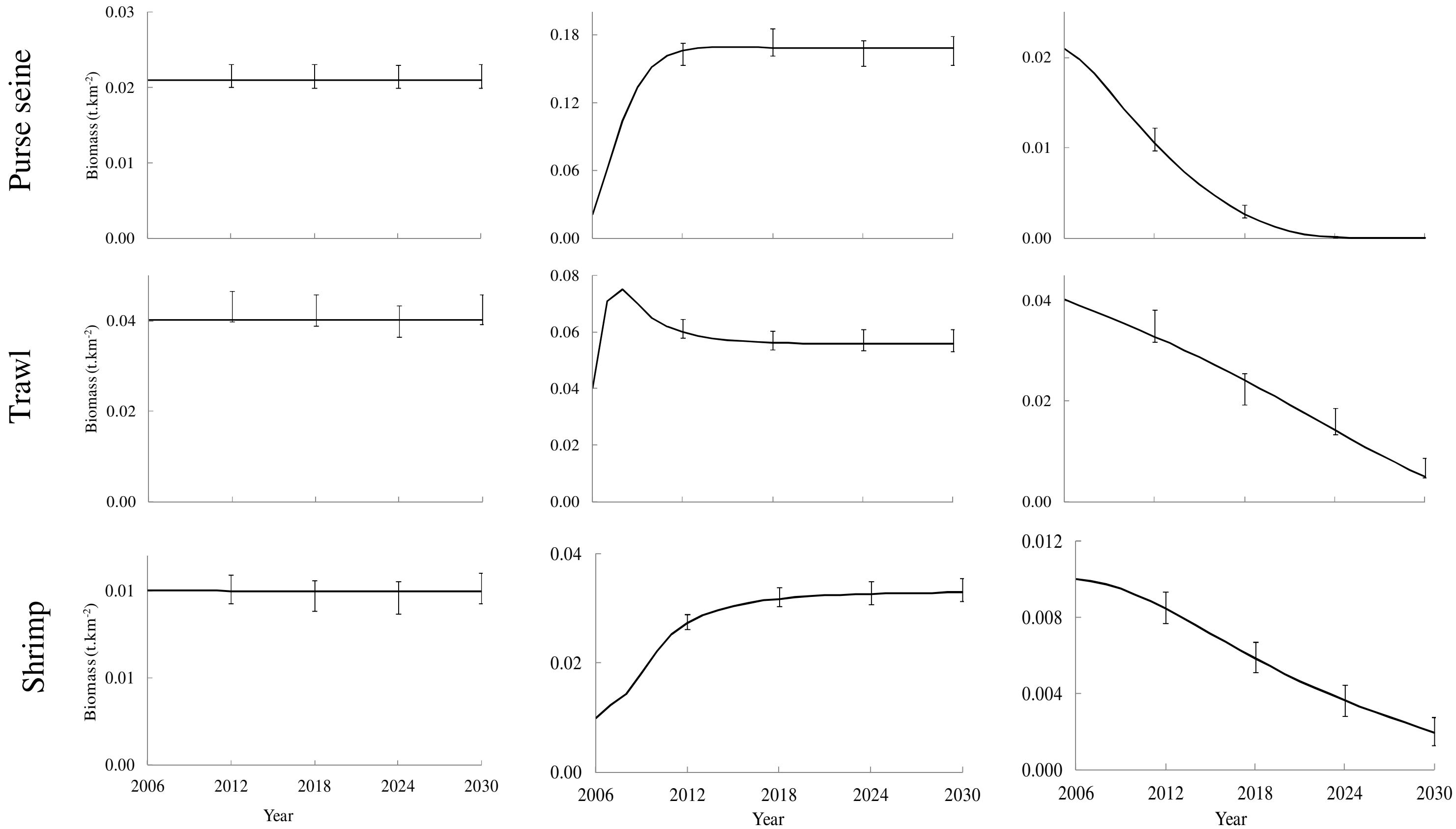


Figure 6.6 Ecosim simulation test at three scenarios (zero, baseline and effort increasing at 5% per year). The lines are the biomasses of the major fishery groups predicted by the model for 24 year simulations from 2006 – 2030, error bars show 1 SD around the mean.

Table 6.3 Biomass depletion risk probabilities for the major fishery groups in the Red Sea below different levels of biomasses, as a ratio of the baseline (2006), at the end of 24 years simulation (2030).

	End state (2030) biomass as a percentage of baseline (2006)						
Groups	5%	10%	15%	20%	30%	40%	50%
Trawler fishes	0	4	38	78	99	100	100
Purse seine fishes	100	100	100	100	100	100	100
Beach seine fishes	0	0	0	0	0	0	0
Handlining fishes	100	100	100	100	100	100	100
Gillnet fishes	0	74	100	100	100	100	100
Sharks	100	100	100	100	100	100	100
Shrimp	0	5	25	47	90	98	100

6.1.1.1 Equilibrium analysis

The equilibrium analysis provided, for all the groups important for fisheries, estimates of equilibrium biomass and catch values at different fishing mortality rates and the value of the current fishing mortality rate in relation to that generating maximum sustainable yield ($F_{msy;}$ Figure 6.7). Gillnet, handlining, shark and purse seine fisheries are operating at fishing mortality rate beyond $F_{msy,}$ while trawl and shrimp are near F_{msy} level. The beach seine fishery was the only fishery operating at a level much lower than F_{msy} (Figure 6.8). The baseline fishing mortality rate of the shark fishery is 3.6 times the optimum calculated by the model, the furthest from F_{msy} of all the fisheries, i.e., the shark fishery is the most depleted resource.

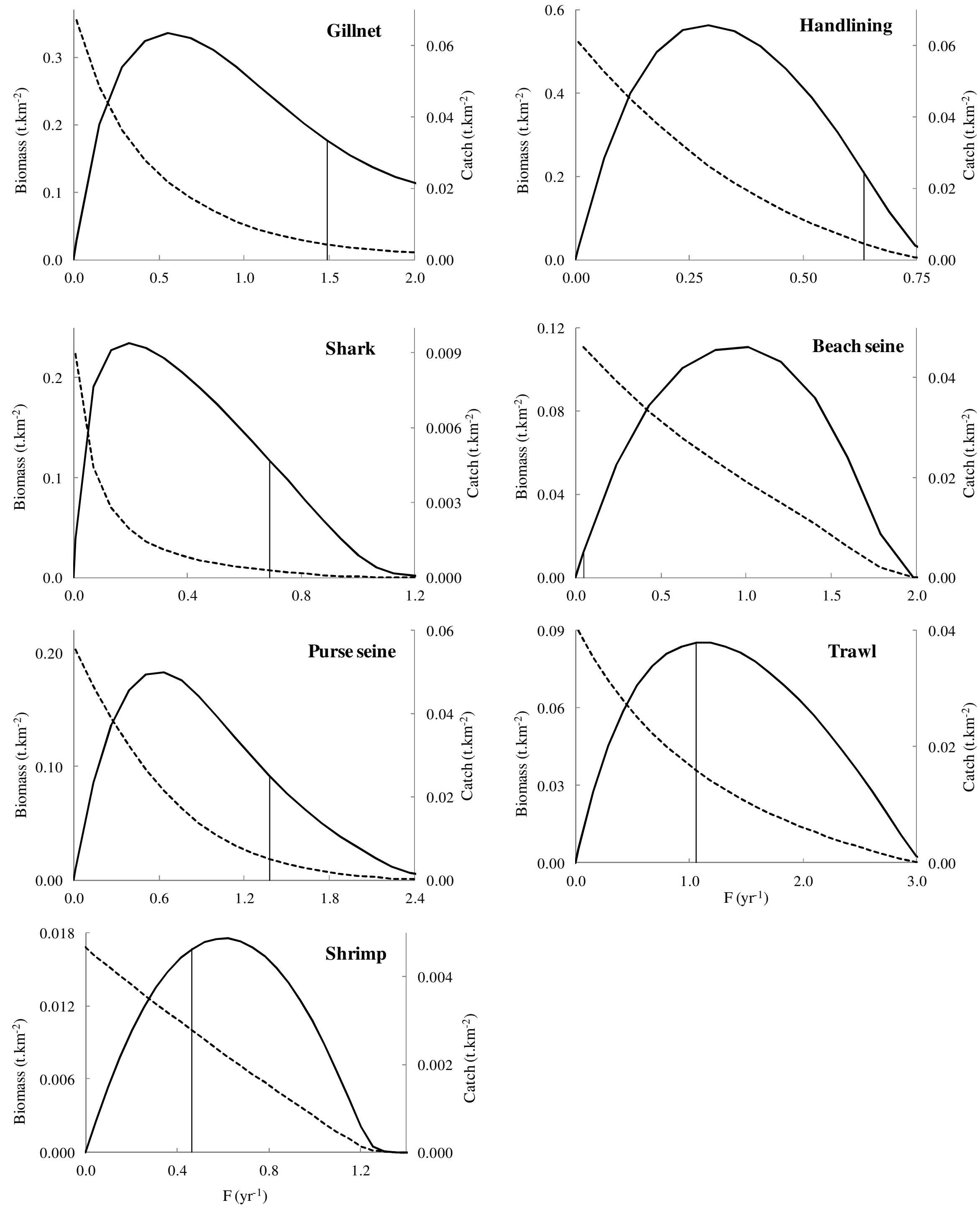


Figure 6.7 Result of the multispecies equilibrium analysis for major Red Sea fishery groups. Curved full line shows surplus yield, broken line shows equilibrium biomass and vertical line is the baseline fishing mortality rate (see text).

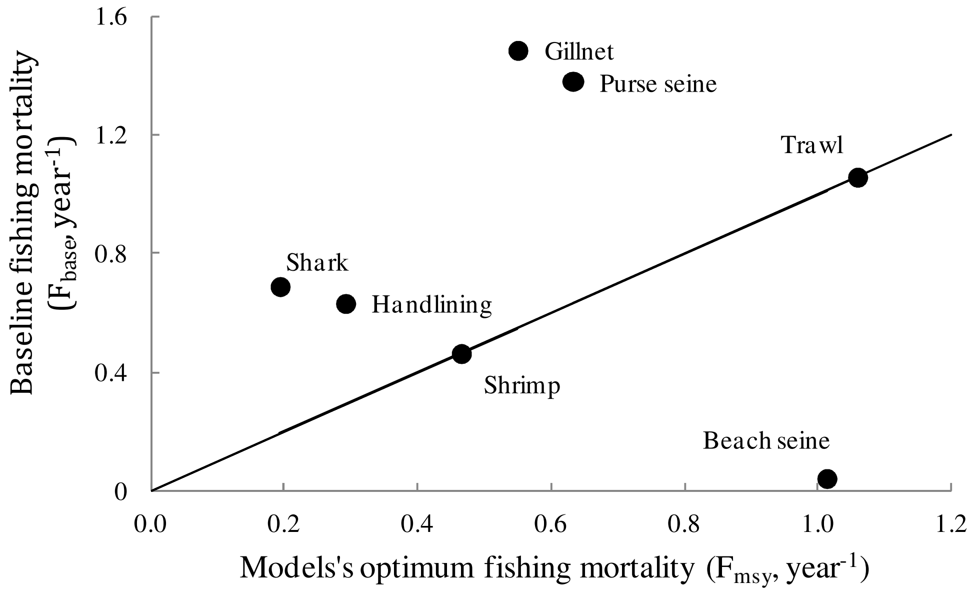


Figure 6.8 Baseline fishing mortality rate (F_{base}) in relation to the optimum fishing mortality calculated by the model (F_{msy}). The 45° line indicates where F_{base} is equal to F_{msy}.

The equilibrium analysis considers multispecies interactions, which is more realistic and closer to the actual ecosystem functioning than single species assessment. For this reason, the yields from multispecies are lower than from single species assessments for all the fisheries except for shrimp (Figure 6.9).

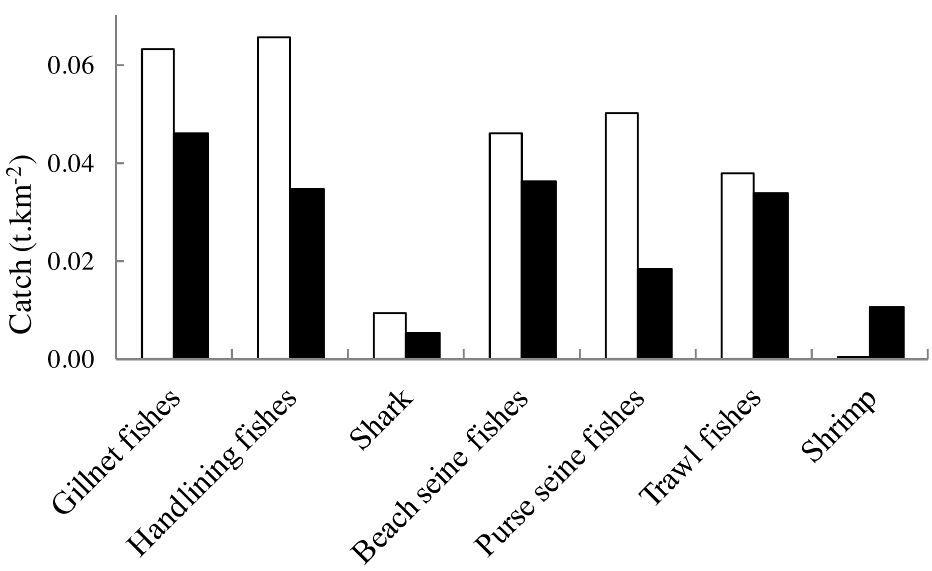


Figure 6.9 Maximum sustainable yields (MSY) comparison of single species (open bars) and multispecies (black bars) equilibrium analysis.

6.1.1.2 Fishery policy exploration

The conflict between artisanal and industrial fisheries was explored by doubling the effort of one sector at a time. This caused, as expected the biomasses of the groups targeted by the respective sector in question to decrease drastically (Figure 6.10). What was interesting and contrary to expectations were the effects of one sector on the other. An increase in the effort of one sector did not decrease the biomass of the groups targeted by the other sector; rather, it increased slightly. When industrial fishing effort was doubled, the increase in the biomass of groups targeted by the artisanal fisheries was higher (Figure 6.10a) than the converse (Figure 6.10b). Doubling the industrial sector did not have an impact on the shark biomass (Figure 6.10a), while beach seine fish biomass benefited from it. The small pelagic beach seine fishes are the main prey for the purse seine fishes, and when the industrial sector effort is doubled, the biomass of the purse seine fishes decreases strongly. This implies that the beach seine fishes experience a predatory release, resulting in an increased biomass.

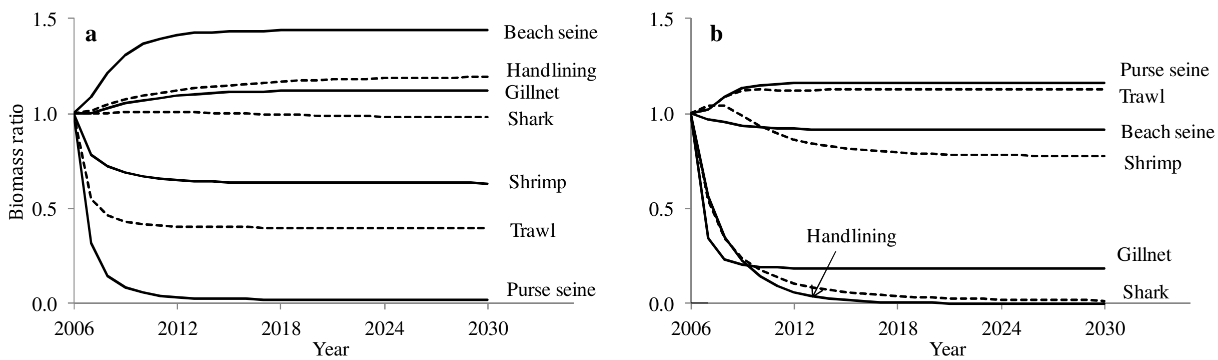


Figure 6.10 Change in the biomass ratios of the major fishing groups as a result of doubling only the industrial fishery effort (a) or the artisanal (b).

6.2 Discussion

The Red Sea, as many coral reef ecosystems, is a complex system with a multitude of interactions among the organisms, and with humans within the ecosystem. The EwE model represents the ecosystem quantitatively and can act as the map to understand the ecosystem in some detail. But the model did not capture all interactions, by far. However, the model gives a reasonable picture of the dominant interactions, and more specifically, about those that affect the fishery, as intended. The Red Sea ecosystem has a large biomass at its base (the primary producers), which tapers off as one ascends the trophic pyramid. All the groups important in the fishery are in the upper part of the food web (upper left corner of Figure 6.1) and have trophic level > 3, except for shrimp. This is reflected in the mean trophic level of fisheries catch, which was 3.4 in 2006 (Table 6.2). This shows that the fishery still can catch top predators, which is uncommon for most of the exploited reef ecosystems of the world (Jackson *et al.*, 2001; Worm *et al.*, 2005).

In terms of the impact of change in biomass of one group on another, increase in shark biomass has the most negative impact on certain groups: cetaceans, birds, turtles, whale shark and rays (Figure 6.3). Shark is the main (for some the only) predator for these groups; hence it has a direct impact on their biomasses through predation. Sea grass has the direct positive impact on the biomass of dugongs, which feed extensively on the sea grass. Most of the other impacts are positive, although at a moderate level. The pedigree value of the Red Sea model is about average for the largest pedigree analysis done yet (Morissette, 2007), despite the fact that some key parameters (especially biomass) were not available. This is surprising, because the Red Sea is reputed to be very data-sparse. It may be mentioned, in this context, that the most comprehensive source of information on the Red Sea was FishBase (www.fishbase.org), especially for the three other main inputs of the model, i.e., P/B, Q/B and diet composition.

Although a high pedigree value, implying abundant sources of input, can lead to better quality model, a more useful validation of a model is its ability to predict independent observations, i.e., fit to a time-series data. Indeed, the fitting of the model to time series catch data was the most important part in validating the EwE model of the Red Sea. During the time series fitting, all parameters and possible interactions (diet matrix and trophic flow parameter vulnerabilities) are scrutinized. At the end of the fitting, some important changes were made to the model. An interesting observation during the fitting was, how difficult it was to fit both the early years of the time series (1950s and 60s), and the final decade. When the whole time series was considered the model at first did not track the independent time series catch at all. It rather produced a horizontal line that went through the observed data. A close examination of the latter data revealed that there was a major shift in the Red Sea fisheries starting in the 1970s. Before the 1970s, most of the fishery, especially the artisanal, was non-motorized and exploited in shallow inshore waters.

With motorization, fishers started to venture out to new fishing grounds further offshore. However, the catch and effort data do not differentiate between inshore and offshore fishing grounds. Hence, the CPUE data do not necessarily reflect trends occurring in the whole ecosystem. Also, Ecosim uses biomass to guide the fitting process. Because a time series of independent observation of biomasses of the different groups does not exist for the Red Sea, the temptation was great to use CPUE data as a proxy for biomass. Using CPUE as a proxy for biomass is problematic. A declining CPUE, while locally accurate, may document only a local depletion, leaving the bulk of the biomass of the group in question unaffected (Hilborn and Walters, 1992) as probably occurred in this case (see below). Thus here, after a few (unsuccessful) attempts to fit the CPUE data, emphasis was given to fitting the catches, as the more reliable data now available from the Red Sea. Also, during the fitting process, emphasis was given to the years after 1970, under the assumption that, after motorization, wider areas of the Red Sea were covered, whereas only the inshore waters were fished before 1970.

This brings us back to the issue of localized depletion in the Red Sea, mainly in fishing grounds near major settlements. Even though the Red Sea still has a relatively high predator biomass, some areas which fishers frequent have shown signs of localized depletion (Tesfamichael, 2001; Tsehaye, 2007). The effect of the spatial distribution of the fishing effort on the fitting procedure can be easily seen by comparing the industrial and artisanal fishery in the Red Sea. Unlike the artisanal fishery, the industrial fishery used motorized vessels from the beginning, giving it a wider coverage. The fits for the industrial fisheries were reasonably good throughout the time series (1950 – 2006), with no change over time, contrary to the artisanal fisheries, where the fits improve markedly (Figure 6.5).

The model stability tests, based on three scenarios (zero, baseline and increasing effort fishing) not only showed that the model was behaving well, but also that the result were moderately precise (+/- 1 SD) when the input parameters were allowed to change within certain range in a random fashion. Decreasing fishing effort, for example, is predicted to have a positive impact on the biomasses of the groups that are fished. On the other hand, if the effort is allowed to increase at the rate it has been increasing the last 10 years (about 5% increase per year), the model predicts that all the groups important to the fisheries (except beach seine fishes) will collapse within the next two decades (Figure 6.6). The probability that the biomasses of the groups falls below 5% of the baseline value is very high (100% for purse seine, handlining and sharks) for all the groups except beach seine fishes. Thus, increasing the effort level by the rate it has been increasing for the last 10 years would have dire consequences in the long term.

These predictions were confirmed by analysing the fishing level of each fishery important group using the equilibrium analysis, which showed that most of the fisheries are operating at an effort level higher than that required to generate MSY (F_{msy}; Figures 6.7 and 6.8), except for beach seines fishes, which is at a very low level, and shrimp and trawl fishes, which operate around F_{msy}. These results are compatible with the general understanding of the situation of the fisheries, and their trends. It seems conflicting that there are still big sized top predators in catches of the Red Sea artisanal fisheries, but the equilibrium analysis shows that the fisheries are operating beyond the MSY level. This is explained by the fact that the big predators are not common in the catches throughout the Red Sea. They are rather common in Sudan and Eritrea, the countries with the least intensity of fishing, which is demonstrated both in Chapters 2 and 3. Even in those countries, the big predators appear in the catches when fishers venture out to newer fishing grounds, otherwise there are evidences of localized depletions (Tesfamichael, 2001; Tsehaye, 2007). The pockets of fishing grounds with still relatively unexploited biomasses are easily overshadowed in the ecosystem modelling analysis which deals with the whole Red Sea. Second, this occurrence of top predators in the catches of the Red Sea fisheries is sometimes taken as an indicator that the Red Sea fisheries are doing better only in comparison to similar ecosystems that are worse than the Red Sea, for example southeast Asia (Christensen, 1998; Pet-Soede *et al.*, 2000) and west Indian Ocean (McClanahan, 1995). However, this comparison can be detrimental because the reference is to a worse scenario rather than to the potential of the Red Sea ecosystem as shows in the EwE model.

Using the ecosystem model results in isolation, as if they were the results of stock assessments, may not be advisable. We cannot expect models to generate precise predictions, but rather give coherent representations of the system in question, and its dynamics (Christensen *et al.*, 2008). For the Red Sea model caution is needed, particularly in conjunction with the equilibrium analyses of the artisanal fisheries, as they may be still reflecting only the limited area where that the fisheries operate, which may not translate easily to the whole ecosystem. This may hold true even after the motorization of artisanal boats and expansion of their fishing grounds. It will be worth examining this hypothesis with an explicit spatial dynamics of the fishing effort, which is not available at the moment.

One example that stands out clearly is the estimated MSY for the beach seine fishery (Figure 6.9) is lower than for the gillnet, handlining and purse seine fisheries (depending on whether one takes the single or multispecies analysis). However, previous stock assessment results indicate that the MSY value of beach seine fishes would be higher than almost all the other fisheries (e.g., Walczak and Gudmundsson, 1975; Giudicelli, 1984). Indeed, it appears that the representation of the beach seine fishery in the Red Sea EwE model suffered from its limited size, and the absence of good data. EwE applications benefit immensely, with regards to the trustworthiness of their prediction, from time series historic fishery data of exploited stocks (Villy Christense, pers. comm.; see also Guénette *et al.*, 2008).

Except for shrimp, all the MSY estimates of the fisheries were lower in the multispecies equilibrium analysis than single species analysis (Figure 6.9). The former is more realistic representation of the system, and that is why an ecosystem based fishery assessment and management can produce a more holistic and reasonable results. One possible explanation for a higher MSY for shrimp in multispecies equilibrium analysis is that shrimp is at the lower trophic level and in multispecies analysis the biomasses of the predators are reduced, which means less mortality by predation, which in turn translates to a higher level of MSY.

Perhaps the most important question about the fisheries situation in the Red Sea is whether artisanal and industrial fisheries interact, and if they do, to what extent. The complaints of the artisanal fishers about the industrial fisheries (which are foreign companies in most of the Red Sea countries) are common and sensitive issue. Although their conflict may have many facets, one of the main aspects of the competition between these two fisheries is the effect of the industrial sector on the catch of the artisanal fisheries. In 472 interviews conducted in the Red Sea countries of Sudan, Eritrea and Yemen with the artisanal fishers, 75% of them blamed increase in effort, which includes both artisanal and industrial, as the reason for decline in their catch (D. Tesfamichael, unpublished data). Most of that blame, however, is laid on the industrial sector. This is the reason why the trophic interactions between groups and fisheries were studied using EwE. The model simulation supported that increase in effort in general is the cause of the decline (Figures 6.6 and 6.10), but did not support the contention that that one sector is causing the decline of the other (Figure 6.10). Actually, to a small extent, the sectors appear to be synergistic, i.e., their interactions are not zero-sum game. This is contrary to the general perception (e.g. in Pauly, 2006); it is also not commonly seen in ecosystem models (Daniel Pauly, pers. comm.). Looking at the mixed trophic impact of the fisheries on each other shows that, the main negative impact of the groups is on themselves (Figures 6.4 and 6.10), but there is no negative impact on others, except for the slight effect that handlining has on the purse seine and gillnet fisheries.

Another crucial insight comes from the nature of the two sectors. They do not target the same groups, thus avoiding direct competition. They operate on groups which inhabit different habitats, and even when they target similar habitat (e.g., pelagic by purse seine, gillnet and beach seine) their gears and operations differ. Trawl and handlining fisheries target mainly muddy and reef habitats, respectively, which are not targeted by any of the other fisheries. Possible conflicts would be among the fisheries that target pelagic species. Purse seiners target small and medium pelagic species, but not close to the shore, while gillnet fishery targets large pelagic species using bigger mesh size gillnets than the mesh size used by purse seiners. The main potential conflict would be between beach seine, which also targets small and medium pelagic fishes, and purse seine, which is shown in the mixed trophic impact analysis (Figure 6.4). This is reflected by the increase in beach seine fish biomass in the simulation when the biomass of purse seine is decreased due to increased industrial fishery effort levels (Figure 6.10a). However, the beach seine fish biomass increase is not very big, because beach seines operate mainly on shallow beaches as opposed to purse seiners which operate in relatively deeper water; thus, there is not overlap of habitats to see a big impact of purse seine on beach seine. Second, at the present, the beach seine fishery is almost non-existent, i.e., the group's biomass is almost at its highest carrying capacity (Figure 6.7) with no room for large increase. For the pelagic species, even if beach seine and purse seine fisheries operate in different habitats and use different gears (mesh sizes), one could argue that the very mobile (or migratory) behavior of the target species would cause mixing and possible conflict. Simulation runs where the fishing pressures of the industrial fisheries (trawl and purse seine) were increased ten folds were run to examine how far the effort can increase before it starts to affect the artisanal fisheries. There was no impact on the biomasses of the groups targeted by the artisanal, except sharks, when the trawl effort was increased ten times.

The lack of major impact among the fisheries is helped by almost non-existent mixed trophic impact among the groups (Figure 6.3). This scenario may not be common in many other ecosystems, but the Red Sea still has a wide range of low and high trophic level fishes appearing in the catch (e.g., the mean trophic level is 3.4, see Table 6.2). A possible hypothesis to explain this singular behaviour of the Red Sea model (and, hopefully, of the Red Sea itself) is that because of the wide range of fish available for the fisheries, they can still target different sections of the ecosystem with no direct competition. One can conjecture that the fewer top predators, the main target of the artisanal fisheries, are available, the more they will start to target lower trophic levels, as they do in many fisheries (Pauly *et al.*, 1998), making them rely on the resources which the industrial sector also exploits. However, it is important to note that these results apply only to the trophic interactions between the industrial and artisanal fisheries. In real life, these two fisheries are not totally separate from each other and there are many non-trophic interactions that are not dealt in with EwE. For example, there are complaints by artisanal fisheries that the industrial fisheries operate close inshore (forbidden in almost all Red

Sea countries) and destroy coastal habitats, and sometimes even the fishing gears of the artisanal fishery. Although, the trophic model of the Red Sea does not deal with such issues, it does deal with an important aspect of the conflict, and thus can be useful, in conjunction with other approaches, for exploring policies for the Red Sea fisheries.

The total catch for 2006, the base year of the model, was 122,370 t (only 95,564 retained), which was calculated to be 0.2 $t{\cdot}km^{-2}$, the unit used in the model. This may not sound high in a global context. Nevertheless, it is significant to the countries in the region. Fish is the main staple food for the coastal communities. It is a cheap source of protein and provides livelihood for the communities. The Red Sea area is very dry and population density is low, which may explain why there are still large sized predators in the catch. Since the countries on the Red Sea coast are generally less industrialized, fisheries can be a good source of employment. The fishery may be expanded further to supply more protein and employment for the local people, but that expansion should target the small pelagic beach seine fishery, all the other fisheries are already at or beyond their sustainable level (Figures 6.7 and 6.8).

CHAPTER 7: Conclusion

The rate at which we are exploiting resources cannot continue at the same level without creating major problems for the ecosystems. We humans interact with the environment and depend on the resources for our basic needs and survival. This has affected our spatial distribution and behavior to an ever greater extent (Mannino and Thomas, 2002). With an ever increasing human population, the issue of resource scarcity has caught the attention of policy makers, academics and the general public. The oceans and other water bodies deliver tremendous services to our life on this planet through temperature regulation, water cycle, transportation, food provisioning, etc. It has increasingly become clear that some of the impacts of our activities can have serious, sometimes detrimental, effects on the environment and the organisms that live there. Fishery resources, similar to forest and grazing pasture, have the potential to regenerate, hence can be categorized as renewable resources. However, they cannot regenerate under any circumstances. Their potential to regenerate is limited and conditioned on how much of the resource is taken and how much is left in the water. In theory, fishery resources can be used sustainably, if the exploitation rate does not compromise the inherent regeneration capabilities of the fish populations. This basic idea highlights the need to understand the resources and our interactions with them, i.e., how much of the resource is there, its regeneration capabilities, how much has been taken away and the consequences of the exploitation. So, fishery sciences developed to address these basic questions.

Our perception or assessment of fisheries evolved through different phases over time, from the thoughts that the bounty of the oceans is infinite and cannot be exhausted (Costanza, 1999; Roberts, 2007) to what we know now where most major stocks of the oceans are declining and exhibit serious depletion problems (Myers and Worm, 2003). Accordingly, fishery science, as an applied science responding to the phenomena around us, evolved in parallel to our changing perceptions of the resources. Many different fishery assessment tools have been developed and likely more will be developed in the future as well. In recent history, fishery science has evolved from the classical single-species stock assessments and their many variations (Beverton and Holt, 1957; Hilborn and Walters, 1992), to multispecies stock assessments (May *et al.*, 1979), and ecosystem-based assessments (Pikitch *et al.*, 2004). The inclusion of socio-economic aspects of the resource users explicitly in assessments is becoming very important (Clark, 1973;

Jentoft *et al.*, 1998; Berkes *et al.*, 2003). Even with the best possible assessment knowledge of fishery resources, in the end, management must deal with humans, not fish (Hilborn, 2007).

The different assessment approaches were developed to address specific questions, pertinent at the time of their development. But later, when more and new questions were raised and the previous tools were deemed not able to address the new issues, opportunities were created for the birth and growth of different approaches; the process continues. The assessment approaches develop not solely out of the questions asked, but also depend on the resources available to accomplish the task and their applicability to the specific context in which they are to be deployed. It is within such context that the Red Sea ecosystem and its fisheries were assessed in this thesis.

7.1 Summary

Each chapter was written to stand as a separate paper, with its own discussion and concluding remarks, and some of them have already been published. Here I will summarize the main contribution of each chapter to the assessment of the Red Sea and how the findings of each chapter fit in the thesis.

I started, in Chapter 2 of the thesis, with the general review of the fisheries in the Red Sea and evaluated their sustainability using standardized scoring procedure of attributes in the ecological, economic, social, technological, and ethical fields. The standardized attributes enabled comparison of the fisheries. The multidimensional scaling employed in analyzing the scores of the fisheries resulted in two-dimensional plots with the relative positions of the fisheries. This was a good starting point because the data need for this analysis is not extensive and most of the information needed to score the fisheries is available from general description, not necessarily quantitative, of the fisheries, which are contained in annual or technical reports (e.g., those issued by FAO). This exercise allowed me to familiarize myself with the fisheries of all the countries in the Red Sea and also understand their performances in several fields, which was a good starting point. However, it was not a very detailed quantitative assessment; for example it did not show change in patterns or rates over time.

In the next Chapter (3) the fishery was assessed based on the information available in the memories of the communities whose livelihoods depend on the Red Sea and its resources. The premise for this chapter was that the absence of written documents on the status of the fisheries can be compensated, at least to a certain extent, by the knowledge stored in the memory of the people involved with the resources. The Red Sea region does not have a strong written culture, but there is a strong oral tradition. The people involved with the extraction of the resources perform observations, although not in the metrics and designs employed by scientific research. The knowledge in the memories of the communities was used to assess the long term changes in status of the resources, using interviews mainly with fishers and also with community elders and fishery administrators. The resources needed for this analysis were more than the assessment done in Chapter 2. One year's field work was needed to interview resource users. The results of Chapter 2 were used to guide the interview procedure, e.g., which fisheries to concentrate on. The main output of this analysis was relative quantitative assessment of the resources over a long period of time. The fisheries can be compared in terms of their relative changes, but not in absolute values.

In Chapter 4, the focus shifted from qualitative and relative quantitative assessments toward quantitative and actual values. The actual catch amount of the Red Sea fisheries was reconstructed from 1950 – 2006. This is a more detailed analysis than the previous two approaches; hence, the resources needed for this assessment were also more than the previous two approaches. Hard quantitative data and detailed knowledge of the fisheries were needed. They were obtained by searching any record of quantitative value of catch, scrutinizing it for any missing information and performing corrections with clear assumptions, given the best knowledge available. The main result of this analysis is the first comprehensive and standardized catch statistics of the Red Sea fisheries by gear and species composition. This is the most basic information needed to carry out quantitative analysis of the fisheries. This is a major achievement and probably the portion which will be most used by researchers and managers. Notably, the results can be used as a baseline reference for future policy choices. However, they cannot be used to quantitatively predict what would happen in the future under different scenarios.

Chapter 5 analysed in detail the unreported catch and the uncertainty associated with its estimation by taking the case study of Eritrea. Unreported catch affects fishery assessment because it causes an underestimation of the actual amount of catch. The estimation was done using major changes in the history of the fisheries, based on the accounts of the fisheries, that would create an incentive or disincentive to misreport catch. The incentives were then converted to actual amounts based on quantitative estimates of the unreported catch as anchor points. Then, the uncertainties around the estimates were calculated using Monte Carlo simulation runs. This assessment gave quantitative estimates of the magnitude of the unreported catch and also the uncertainty of those estimates, which is a significant addition to the reconstruction of time series catch in Chapter 4.

The last Chapter (6) consists of an assessment of the Red Sea in an ecosystem-based framework, which is the latest approach in fisheries assessment. It used a holistic, quantitative ecosystem modelling approach to assess the ecosystem and the impacts of human interaction, i.e., fisheries. As in the other chapters, the main focus of the assessment was the fisheries. This chapter has the most detailed assessment of the Red Sea. It quantifies not only the fish species that are very important in the fisheries, but also all the other organisms in the ecosystem. In addition, it quantifies the interactions among the organisms and the fisheries. As far as the fisheries are concerned, it presents quantitatively the actual values of the level of exploitation in relation to the potential of the resources. It also reproduces the changes in the fisheries since 1950. And the most important for management is, it can predict what will happen to the fisheries and ecosystem under different scenarios. This is the most significant assessment tool of this chapter, and one that none of the previous chapters could match. It is also the most important section to be considered in any decision-making process. All the previous chapters assess what has happened to the system up to the present, which is important for knowing where we are and how far we have exploited the resources; however, they are not equipped to quantify the future possible scenarios. The ecosystem-based assessment, on the other hand, combines the past up to the present and forecasts the future as well. The data need for this assessment was the most extensive. It incorporates all the information from the previous chapters plus detailed ecological data. It benefited from the long time series of historic data of the Red Sea fisheries assessment and combined that with the ecological data for detailed and comprehensive analysis in actual (not relative) quantitative values covering the past to the present and the future.

The analyses demonstrated an incremental increase in the details of the assessment and the corresponding need for resources (data, manpower and time). It gives a wide range of possibilities from which one can choose to carry out the assessment to answer specific questions with clear understanding of what is needed and available, and the limitations of the assessments. For example, at one end of the spectrum, for a quick and wide but not detailed understanding of fisheries, the rapid appraisal of fisheries (Rapfish) can accomplish the task with minimum effort. At the other end of the spectrum, for detailed quantitative analysis one can utilize the ecosystem-based assessment with its high demand for resources. What is interesting in the analyses is the similarity and complementarity of the assessment results. All the analyses, except the rapid appraisal, which does not have time dynamics, showed decline in the resources. The changes are expressed in different ways, for example in the analysis of interviews, it is relative change, which was highlighted in Figures (3.3 and 3.4), while it was the actual value in relation to the potential of the resources for the ecosystem modelling (Figure 6.7). The only exception, i.e., a fishery that is not declining, is the beach seine fishery, which is a special case, because the fishery used to be active in the early 1950s but was largely abandoned for marketing reasons. Hence, the decline in its catch (Figure 4.4) is not due to depletion of the resource (Figure 6.7).

The most striking result from all the analyses is the assessment of sharks. It ranked as one of the worst in the rapid appraisal of the fisheries in the ecological field (fishery 26 Figure 2.1), has the highest decline of catch rate in the interview analysis (slope of Figure 3.3c), shows high depletion in the ecosystem analysis (Figures 6.7 and 6.8), and could face worst consequences in the future if the fishing effort intensifies (Figure 6.10b). When the catches of sharks from the catch reconstruction (Figure 3.4 and Table C.5) were divided by the total effort of gillnet and handlining fisheries (Table E.7 in the Appendix), which both target sharks, the catch rate (CPUE) of sharks was obtained. The CPUE then was compared to the catch rates from the interview analysis (Figure 7.1). The decline rate according to the interview data is 10.3% per year (Figure 7.1a); while when a continuous regression line is fitted to the CPUE, the broken line in Figure (7.1b), the decline rate is 8.1% per year. A close scrutiny of the CPUE data shows two sets of data: one starting from 1950 – 1964, where the decline is very small, and a second set from 1965 – 2007 where the CPUE peaked, then declined drastically. The main reason for this difference is the introduction of motors for boats in the beginning of the 1960s (Appendix E.2.1). So, if two separate regression lines are fitted (full lines in Figure 7.1b), the decline rate for the latter part, which overlaps with the period of the interview, is 11% per year, similar to the decline rate according to interviews (10.3% per year). This is a good example to show that an assessment with fewer resources (interview in this case) can be as informative as a detailed and resource-intensive approach (the catch reconstruction). Waiting for a detailed assessment and not taking any action until that is fulfilled is a bad excuse for inaction. However, this is not to argue that the less detailed analyses can fully replace the detailed analyses.

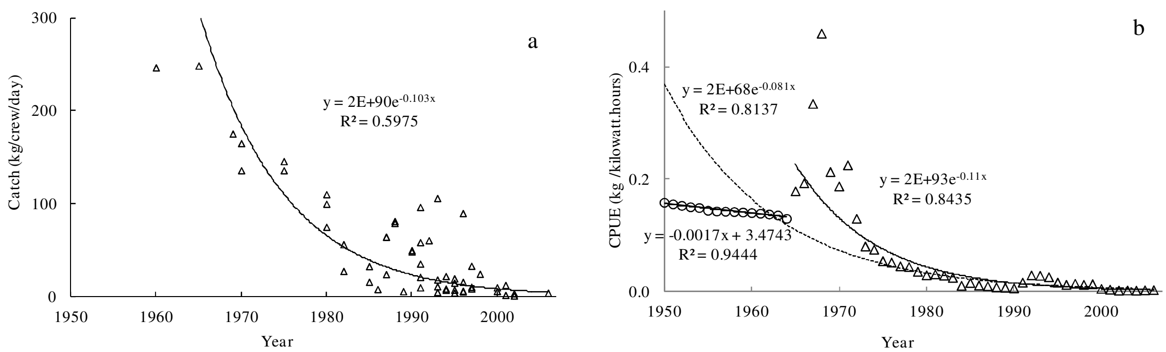


Figure 7.1 Change in catch rate of shark fishery from interview (a) and catch reconstruction (b).

7.2 Data, knowledge, management and conservation

Comparison of the different resource assessment approaches raises the question of how much information and knowledge is needed in resource assessment for proper management actions to be taken in order to conserve resources and livelihoods. The quantitative stock assessment tools used in fishery assessment demand a lot of data, which is not available for most of the fisheries of the world (Froese *et al.*, 2012). The situation is worse in many developing tropical countries, of which the Red Sea is a part. The resources needed to collect detailed fishery data and analyze them are not readily available and may not be top priority in many developing countries. The situation is further complicated, as compared with temperate systems, by the multispecies and multiple gears nature of the fisheries. This is a practical challenge faced by both researchers and practitioners of tropical fisheries, and it may not vanish easily in the future either. Creative and practical approaches will be needed to overcome this challenge and give information for effective actions.

An interesting aspect to note is the source of information. The societies around the Red Sea do not have a strong written tradition; however, that does not mean there is no information and knowledge useful for assessment. The societies have very strong oral tradition and if accessed systematically, as shown for example in Chapter 3, it can be a source of important insights. The people who interact with the resources experience the events and record them in their memories. Such information can be as good as an independent research observation (Pauly, 1995). When such observations are shared with others it creates a collective memory and knowledge. It will be beneficial to use such knowledge, and not using them because, for example, they do not fit in to the framework of scientific research will be losing an opportunity, which in some cases could be the only one (Johannes *et al.*, 2000; Soto, 2006). Scientists are becoming increasingly interested in accessing such knowledge and some methodologies are being developed, although they are still crude and more refinements are needed. Such knowledge, however, should be used with caution. Some of the understandings, legends or myths may not be realistic. For example, during my interviews with the fishers, the idea that the sea can never be polluted because it is so vast was a common saying in the communities. If the main objective of fisheries assessment is to manage the resources so that they are conserved and sustainably used, using any knowledge will be an asset in the process. Incorporating the resource users in the process helps not only as a source of information, but also to understand their perceptions, which is important for the success of any management scheme.

7.3 Contextualizing science

In additional to data and resources availability, another serious challenge faced by fishery researchers in tropical countries is the applicability of the commonly used assessment tools. Fishery science, as we know it now, developed in temperate systems. However, those approaches proved not directly applicable in tropical systems. The design of the tools and their implementations are characteristically temperate. A typical issue that comes to the forefront is the use of age-based assessments. It is easier to age temperate fishes using growth rings in otoliths, but not for tropical fishes. Of course, there are some clever modifications made to adopt methods to tropical situations, such as using length rather than age (Pauly and David, 1981). Yet, the tropical research tools and knowledge have not developed much further than this. Moreover, even at the moment, most of the research in tropical systems is done by scientists and organizations from the developed nations, in Europe, North America and Australia. Disconnection between the important issues on the ground and the priorities taken by the initiatives is not uncommon (Anderson *et al.*, in press). For example, during my field trip interviews, fishers and community elders repeatedly mentioned that the immediate attention needed in the Red Sea is the conservation of sharks, which is also demonstrated by the different assessment tools described in this thesis. However, none of the few development/research initiatives in the Red Sea is focused on sharks. The result is that local communities feel sidelined from the actual process and their compliance with any management regulations is very low. Taking these important issues in practical assessment and conservation in places like the Red Sea and integrating them in the assessment and management of fisheries will help to move forward in the successful application of the science, which will lead to fisheries really becoming the ‘applied’ science it claims to be.

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Appendices

Appendix A Supplementary material for Chapter 2

Table A. 1 Rapfish attributes in their respective fields and notes on their scoring.

Attributes	Good	Bad	Notes
Ecological analysis			
Exploitation status	0	4	Under- (0); fully- (1); heavily- (2); or over-exploited (3); almost completely collapsed (4)*
Recruitment variability	0	3	COV low <20% (0); medium 20-60% (1); high 60-100% (2); very high >200% (3)
Change in trophic level	0	2	Is the trophic level of the catch decreasing: no (0), somewhat, slowly (1); rapidly (2)
Migratory range	0	2	Number of jurisdictions (international included) encountered during life history: 1-2 (0); 3-4 (1); >4 (2)
Range collapse	0	3	Is there evidence of geographic range reduction: no (0); a little (1); a lot, fast (2); very great, rapid (3)*
Size of fish caught	0	2	Has average fish size landed changed in past 5 years; no (0); yes, a gradual change (1); yes, a rapid large change (2)
Catch before maturity	0	2	Percentage caught before size/age of maturity: none (0); some (>30%) (1); lots (>60%) (2)
Discarded by-catch	0	2	Percentage of target catch: low 0-10% (0); medium 10-40% (1); high >40% (2)
Species caught	0	2	Number of species caught (retained and discarded): low 1-10 (0); medium 10-100 (1); high >100 (2)

Attributes	Good	Bad	Notes
Economic analysis			
Fisheries in GDP	2	0	Importance of fisheries sector in the economy: low (0); medium (1); high(2)
Average wage	4	0	Do fishers make more or less than the average person? Much less (0); less (1); the same (2); more (3); much more (4)
Limited entry	4	0	Includes informal limitations: Open Access (0); Almost none (1); very little (2); some (3); lots (4)
Marketable right	2	0	Marketable right/quota/share? (0); some (1); mix (2); full ITQ, CTQ or other property rights (2)
Other income	0	3	In this fishery, fishing is mainly: casual (0), part-time (1); seasonal (2); full-time (3)
Sector employment	0	2	Employment in formal sector of this fishery: <10% (0); 10-20% (1); >20% (2)
Ownership/Transfer	0	2	Profit from fishery mainly to: locals (0); mixed (1); foreigners (2)
Market	0	2	Market is principally: local/national (0); national/regional (1); international (2)
Subsidy	0	4	Are subsidies (including hidden) provided to support the fishery?: no (o); somewhat (1); large subsidies (2); heavily reliant (3); almost completely reliant on subsidies (4)*
Social analysis			
Socialization of fishing	2	0	Fishers work as: individuals (0); families (1); community groups (2).
New entrants into the fishery	0	3	Growth over past ten years: <10% (0); 10-20% (1); 20 - 30% (2); >30% (3)
Fishing sector	0	2	Households containing fishers in the community: few, <10% (0); some, 10-30% (1); many, >30% (2)
Environmental knowledge	2	0	Level of knowledge about the fishery resource and its ecosystem and environment: none (0); some (1) ; lots (2)
Education level	2	0	Education level compared to population average: below (0); at (1); above (2)
Conflict status	0	2	Level of conflict with other sectors: none (0); some (1); lots (2)
Fisher influence	2	0	Strength of direct fisher influence on actual fishery regulations: almost none (0); some (1); lots (2)

Attributes	Good	Bad	Notes
Fishing income	2	0	Fishing income as % of total family income: <50% (0); 50-80% (1); >80% (2)
Kin participation	4	0	Do kin sell and/or process fish? None (0); very few relatives (1-2 people) (1); a few relatives (2); some relatives (3); many kin (4)
Technological analysis			
Trip length	0	4	Average days at sea per fishing trip. 1 or less (0); 2-4 (1); 5-8 (2); 8-10 (3); more than 10 (4)
Landing sites	0	3	Are landing sites: dispersed (0); somewhat centralised (1); heavily centralised (2); distant water fleet with little, or no local landings (3)
Pre-sale processing	2	0	Processing before sale, e.g. gutting, filleting, salting: none (0); some (1); lots (2)
Onboard handling	3	0	None (0); some (e.g. salting, boiling) (1); sophisticated (e.g. flash freezing, champagne ice) (2); live tanks (3)
Selective gear	2	0	Device(s) and/or handling of gear to increase selectivity? Few (0); some (1); lots (2)
FADS	0	1	Fish attraction devices: not used (0); bait is used (0.5); used (1)
Vessel size	0	4	Average length of vessels: <5 m (0); 5-10 m (1); 10-15 (2); 15-20 (3); >20 (4)
Change in catching power	0	4	Have fishers altered gear and vessel to increase catching power over past 5 years?: No (0); very little (1); little (2); somewhat (3); a lot, rapid increase (4)
Gear side effects	0	3	Does gear have undesirable side effects (e.g. cyanide, dynamite, trawl); no (0); some (1); a lot (2); fishery dominated by destructive fishing practices (3)*
Ethical analysis			
Adjacency and reliance	3	0	Geographical proximity & historical connection: not adjacent/no reliance (0); not adjacent/some reliance (1); adjacent/some reliance (2); adjacent/strong reliance (3)
Alternatives	2	0	Alternatives to the fishery within community: none (0); some (1); lots (2)

Attributes	Good	Bad	Notes
Equity in entry to fishery	2	0	Entry based on traditional/historical access/harvests? not considered (0); considered (1); traditional indigenous fishery (2).
Just management	4	0	Inclusion of fishers in management: none (0); consultations (1); co-mgmt/gov't leading (2); co-mgmt/comm. leading (3); genuine co-mgmt with all parties equal (4)
Mitigation – habitat destruction	4	0	Attempts to mitigate damage to fish habitat: much damage (0); some damage (1); no ongoing damage or mitigation (2); some mitigation (3); much mitigation (4)
Mitigation – ecosystem depletion	4	0	Attempts to mitigate fisheries-induced ecosystem change: much damage (0); some damage (1); no damage or mitigation (2); some mitigation (3); much mitigation (4)
Illegal fishing	0	2	Illegal catching/poaching/transshipments: none (0); some (1); lots (2)
Discards & wastes	0	2	Discard and waste of fish: none (0); some (1); lots (2)

* called "killer" attribute scores and shift all scores in that evaluation field to the "bad" score. For ecological analysis, if the sum of the score of the two "killer" attributes exceeds 5, then all scores are shifted to "bad".

Appendix B Supplementary material for Chapter 3

Questionnaire used to collect data on historic and present utilization of fishery resources in the Red Sea.

GENERAL BIO-DATA

Code_________ Date________ Location____________________________

1. Age/date of birth______________ 2. Gender: F ☐ M ☐

3. Place of birth ________________ Current place of residence ______________

When did you move?____

4. Occupation: Boat owner ☐ Skipper ☐ Crew ☐ Retired/when_________

Other___________________________

Did you change occupation? Yes ☐ No ☐

Do you do other jobs besides fishing? ____

Education (formal) level____________

How long have you been in fishing (start - end?)_________________________________

How many generations has your family been in fishery? (Circle one) 1 2 3 4 >4

Number of family members involved in fishing?_________________________________

Any interruption in your fishing career, when and for how long?____________________

Interviewer's remarks

EFFORT DATA

Code___________

Crew size____________________

Boat: Type: Sambuk ☐ Huri ☐ Other____________

Size__________________

Engine: Inboard ☐ Outboard ☐ HP______________

Gears: Gillnet

Gillnet dimensions_______________ Mesh size_________

Average No. of nets used per setting:_______________________

Hook and line

No. of hooks per line?_______ Hook size_________

Do you use circle hooks: Yes ☐ No ☐

How many people are directly involved in handlining?____________________

What bait do you use?____

How do you get the bait?____

How long, on average, did it take you to go to the fishing ground?

Present____________ Past_____________

*How long was a single trip (average or range in days?)*___________________________

Anything else you would like to tell?

Interviewer's remarks

CATCH DATA

Code__________

The best catch ever you recall:

Kg __________

Boxes________ Size of box (kg)_______

Sacks________ Size of sack (kg)______

Number: Species 1_________ Length (average or range in cm)_________

Species 2_________ Length (average or range in cm)_________

Species 3_________ Length (average or range in cm)_________

Species 4_________ Length (average or range in cm)_________

Species 5_________ Length (average or range in cm)_________

Estimate of all other minor species (kg)__________________________

Other units_____________________________

Size of largest fish ever caught (cm)___________ Species_________________________

Effort of best catch recalled:

Crew size:_____________________

Trip length (days)_______________

Average/typical catch rate when you started fishing______________________________

Average/typical catch rate at the moment (in the same unit as previous question)_______

Anything else you would like to tell?

Interviewer's remarks

Appendix C Supplementary material for Chapter 4

Table C. 1 Red Sea reconstructed catch (t) by sector, compared with the Red Sea total catch data submitted to FAO by member countries.

	Artisanal		Industrial			
Year	Categorized	Uncategorized	Retained	Discard	Uncategorized	FAO
1950	47662	3595	503	1481	0	12913
1951	47651	3399	523	1517	0	13913
1952	48307	3841	543	1551	0	19499
1953	48405	3710	564	1582	0	19806
1954	48598	3519	584	1612	0	21234
1955	48436	3465	604	1640	0	24561
1956	45448	3549	393	966	0	24613
1957	41912	3084	1698	4794	0	25986
1958	38827	3068	1877	5084	0	25774
1959	35408	3401	1925	5101	0	29689
1960	34396	3427	3967	3063	0	30383
1961	38043	3218	7584	6668	0	34595
1962	34721	3414	13441	11533	0	46102
1963	34114	3643	14813	16080	0	44988
1964	36377	3790	12295	20090	0	40665
1965	46018	4059	12040	20378	0	42540
1966	49710	4217	9892	13096	0	40884
1967	45250	4025	11066	11862	0	40472
1968	43745	3699	12363	10776	0	38245
1969	45854	5012	13732	9796	0	38820
1970	50295	4574	15765	11514	0	40639
1971	51193	3793	18192	10366	0	46462
1972	42355	4238	17996	11893	0	43358
1973	37271	3934	6132	6468	0	31470
1974	39606	3757	17878	6777	0	34322
1975	39926	3291	16528	13303	0	30772
1976	40502	3430	25397	12838	0	35974
1977	41378	2917	20694	10633	0	33498
1978	45823	3090	19633	10091	0	36049
1979	45660	6276	24564	7634	0	44875
1980	43695	5530	18365	8415	0	45133

Year	Artisanal		Industrial			FAO
	Categorized	Uncategorized	Retained	Discard	Uncategorized	
1981	48919	5928	17136	9037	0	47075
1982	51249	6329	21140	9737	104	44035
1983	45036	5147	28993	9283	218	51101
1984	45155	6235	32149	8595	320	49436
1985	54087	5531	24846	8303	434	64186
1986	57110	5213	23151	10090	546	65136
1987	64211	7692	25797	8419	674	70746
1988	68847	9060	28962	10004	483	78778
1989	74329	9962	38956	8046	713	96197
1990	71368	8145	38536	7501	606	99145
1991	84697	9912	34687	10498	672	109716
1992	88693	13140	35596	8669	808	114251
1993	102024	17238	43059	10517	794	127653
1994	100188	15133	32951	17210	822	133493
1995	82058	14008	35931	25220	779	133649
1996	68123	11099	32699	24336	798	128270
1997	86853	15486	35060	27021	980	137474
1998	84980	10628	32642	27340	851	136554
1999	83150	9983	36073	31550	1054	158399
2000	60614	6330	52781	34087	1362	148643
2001	61794	5926	45650	36736	1287	147144
2002	67675	10952	48473	39632	1467	145372
2003	61516	7193	47656	42742	1688	138609
2004	57757	9374	47859	35279	1595	133193
2005	60450	8811	34966	30778	722	116503
2006	62014	8347	36125	26806	1167	124057

Table C. 2 Catch (t) composition of reconstructed Red Sea handlining fishery.

Year	Emperors	Groupers	Snappers	Jacks	Barra-cuda	Bream	Parrot fishes	Cobia	Grunts	Cutlass fish	Rabbit fish	Goggle eye	Surgeon fish	Wrasses	Scom-bridae	Tunas	Goat fish	Uni-corns	Others
1950	1008	737	1414	1189	368	264	280	81	0	66	0	0	6	0	6	3	0	5	187
1951	1026	749	1419	1195	370	268	280	82	0	66	0	0	6	0	7	3	0	5	187
1952	1046	760	1424	1200	372	273	280	83	0	66	0	0	6	0	8	4	0	5	187
1953	1066	772	1430	1205	375	277	280	85	0	66	0	0	6	0	8	4	0	5	187
1954	1097	797	1452	1232	383	281	287	87	0	68	0	0	6	0	9	5	0	5	187
1955	1110	822	1468	1259	385	286	294	84	0	69	0	0	6	0	9	5	0	5	187
1956	1143	846	1492	1286	395	290	301	86	0	71	0	0	6	0	10	5	0	5	187
1957	1177	871	1515	1313	404	295	308	88	0	73	0	0	6	0	11	6	0	5	187
1958	1211	896	1539	1340	413	299	315	91	0	74	0	0	6	0	11	6	0	5	187
1959	1245	920	1562	1367	422	303	322	93	0	76	1	0	7	0	12	7	0	5	187
1960	1296	962	1643	1394	432	308	329	95	0	77	1	0	7	0	12	7	0	5	197
1961	1331	987	1668	1421	441	313	336	98	0	79	1	0	7	0	13	8	0	5	197
1962	1351	995	1634	1448	451	317	343	100	0	81	1	0	7	0	14	8	0	5	187
1963	1386	1019	1658	1474	461	321	350	103	0	82	1	0	7	0	14	9	0	5	187
1964	1388	1007	1633	1440	454	326	337	105	0	79	1	0	7	0	15	9	0	5	187
1965	1497	1116	1769	1607	501	331	390	107	0	92	1	0	8	0	15	10	0	5	187
1966	1624	1243	2067	1692	525	335	416	109	0	98	1	0	8	0	16	10	0	5	228
1967	1699	1314	2153	1796	555	339	448	111	0	105	1	0	9	0	16	11	0	5	228
1968	1789	1403	2261	1930	593	343	490	113	0	115	1	0	10	0	17	11	0	5	228
1969	1911	1529	2417	2122	646	346	552	115	0	130	1	0	11	0	18	12	0	5	228
1970	1936	1545	2425	2127	649	349	552	117	0	130	1	0	11	0	18	12	0	5	238
1971	1951	1562	2431	2131	649	351	552	117	0	130	1	0	11	0	19	13	0	6	249
1972	1999	1605	2475	2180	664	354	566	120	0	133	1	0	12	0	19	13	0	6	260
1973	2076	1649	2529	2230	689	356	581	128	0	137	1	0	12	0	20	14	0	6	271
1974	2190	1692	2595	2280	726	360	596	145	0	140	1	0	12	0	20	14	0	7	281
1975	2345	1736	2675	2329	777	363	610	171	0	144	1	0	12	0	21	15	0	7	292
1976	2455	1815	2763	2389	808	366	625	183	0	147	1	0	13	0	22	15	0	11	382
1977	2461	1721	2458	2393	837	371	625	202	0	147	1	0	13	0	22	15	0	10	305
1978	2783	2043	2886	2909	985	379	790	211	0	186	1	0	16	1	23	16	1	11	317
1979	3929	2883	2983	2623	1168	626	694	447	63	163	1	316	14	1	23	16	1	16	342

Year	Emperors	Groupers	Snappers	Jacks	Barra-cuda	Bream	Parrot fishes	Cobia	Grunts	Cutlass fish	Rabbit fish	Goggle eye	Surgeon fish	Wrasses	Scom-bridae	Tunas	Goat fish	Uni-corns	Others
1980	3846	2841	2915	2452	1105	629	634	435	61	149	1	308	13	0	24	7	0	7	477
1981	4170	3257	2750	2751	1415	674	588	501	70	375	2	354	12	1	21	27	1	21	706
1982	4505	3248	2825	2738	1475	695	588	548	77	375	2	387	12	1	19	17	1	18	638
1983	3613	3172	1759	2608	1173	409	449	49	0	550	4	0	9	2	29	17	2	0	803
1984	4063	2914	2905	2605	1629	413	310	209	0	506	3	513	6	8	22	14	2	12	597
1985	6175	4869	3808	3145	2256	1133	209	1084	185	628	4	416	4	21	25	17	2	12	559
1986	6424	4438	3835	3242	2133	1160	218	649	168	654	4	482	4	22	22	15	2	11	538
1987	6843	5238	4222	3945	2612	1953	278	474	19	833	6	0	6	28	20	13	3	11	503
1988	7354	5606	4450	4201	2730	2011	300	435	73	900	6	0	6	30	19	12	3	10	469
1989	7848	6059	4271	4201	2957	1957	300	454	83	900	6	0	6	30	23	16	3	10	434
1990	7613	6040	3591	3902	2940	1658	278	408	82	833	6	0	6	28	28	20	3	0	495
1991	8654	5741	4567	3885	3089	2432	278	687	379	833	6	0	6	28	17	10	3	0	546
1992	8918	6454	5190	3870	3569	2353	278	1116	676	833	6	0	6	28	11	5	3	0	623
1993	10323	7381	7459	4136	4089	3678	300	1514	900	900	6	0	6	30	17	10	3	0	578
1994	10164	7240	6347	4127	3745	3017	300	1532	1369	900	6	0	6	30	15	9	3	0	568
1995	7587	5012	4090	2366	2107	2501	516	1366	2170	361	688	0	103	138	15	8	34	0	631
1996	7224	5723	3505	2847	1792	2039	399	1110	1574	360	599	0	103	137	17	11	34	0	713
1997	8577	6127	4347	2841	2213	2730	451	1434	2367	406	877	0	116	155	19	13	39	0	579
1998	8005	6331	1988	2796	2401	599	449	1622	3844	405	514	0	116	154	13	7	39	0	619
1999	8056	6359	2220	3401	2634	593	482	1547	2727	226	545	0	198	137	8	3	30	0	738
2000	5100	7404	2202	3285	1712	582	464	236	280	218	525	0	191	132	9	4	29	0	705
2001	6439	6778	2262	3551	2035	602	509	1170	267	239	575	0	209	144	10	5	31	0	699
2002	5952	6479	2431	3334	1910	582	474	132	411	223	536	0	195	134	10	5	29	0	724
2003	5717	4910	1860	3198	2172	566	451	155	280	212	510	0	185	128	10	4	28	0	609
2004	4947	4443	2354	2845	1946	464	278	146	329	0	222	0	186	87	9	4	10	0	791
2005	5692	5699	1473	3274	2375	478	301	270	396	0	237	0	226	77	10	5	19	0	639
2006	6180	6235	2136	2956	2421	504	393	390	514	0	248	0	224	77	8	3	16	0	773

Table C. 3 Catch (t) composition of reconstructed Red Sea gillnet fishery.

Years	Kingfish	Indian mackerel	Tunas	Jacks	Mullets	Queenfish	Barracuda	Bream	Rays	Rabbit fish	Guitar fish	Other Scombridae	Parrotfish	Others
1950	2778	3827	804	565	1008	158	130	0	242	97	161	3	9	0
1951	2801	3883	810	573	1016	160	132	0	245	98	163	4	11	0
1952	2829	3951	818	584	1023	163	134	0	250	99	166	4	12	0
1953	2859	4024	826	594	1031	166	137	0	254	101	170	4	14	0
1954	2923	4107	845	606	1050	170	139	0	260	102	173	4	16	0
1955	2904	3987	842	595	1069	164	136	0	252	103	168	5	17	0
1956	2976	4089	863	608	1088	169	139	0	258	105	172	5	19	0
1957	3047	4190	884	622	1107	173	142	0	264	106	176	5	21	0
1958	3120	4293	905	636	1126	177	146	0	271	107	181	6	22	0
1959	3194	4399	926	650	1145	181	149	0	278	109	185	6	24	0
1960	3269	4508	948	664	1165	186	153	0	285	110	190	6	26	0
1961	3346	4622	970	679	1185	191	156	0	292	111	195	6	27	0
1962	3425	4741	993	695	1204	196	160	0	299	113	200	7	29	0
1963	3503	4858	1016	710	1222	200	164	0	307	114	205	7	30	0
1964	3491	4964	1009	725	1209	205	168	0	314	115	209	7	32	0
1965	3769	5093	1096	739	1304	210	172	0	321	117	214	8	34	0
1966	3925	5201	1144	753	1354	214	175	0	327	118	218	8	35	0
1967	4107	5307	1201	765	1414	218	178	0	333	120	222	8	37	0
1968	4332	5415	1271	777	1488	222	181	0	339	121	226	9	39	0
1969	4644	5532	1369	789	1594	225	184	0	345	121	230	9	40	0
1970	4683	5625	1379	801	1598	229	187	0	351	122	234	9	42	0
1971	4683	5625	1380	802	1601	229	187	0	351	123	234	9	44	0
1972	4787	5727	1411	814	1629	233	190	0	357	123	238	10	45	0
1973	5015	6127	1475	859	1657	250	203	0	383	124	255	10	47	0
1974	5397	6902	1580	945	1686	283	228	0	433	125	289	10	49	0
1975	5955	8102	1730	1078	1714	334	267	0	511	126	341	11	50	0
1976	6251	8668	1812	1141	1743	358	286	0	547	127	365	11	52	0
1977	6665	9559	1909	1245	1753	396	318	0	605	128	404	37	54	34
1978	7558	10008	2187	1291	2036	412	331	0	630	131	420	38	55	34
1979	6228	5422	1838	1431	1891	376	592	241	0	133	0	38	57	34

Years	Kingfish	Indian mackerel	Tunas	Jacks	Mullets	Queenfish	Barracuda	Bream	Rays	Rabbit fish	Guitar fish	Other Scombridae	Parrotfish	Others
1980	5901	5268	1727	1406	1808	367	579	235	0	135	0	48	61	48
1981	7047	6085	1849	1591	1676	422	663	270	0	138	0	44	57	44
1982	7374	6615	1036	1713	1690	461	724	295	0	141	0	47	63	49
1983	6888	8298	1550	1528	1410	0	308	0	0	143	0	83	50	89
1984	7665	5044	1287	995	1283	373	667	0	0	144	0	69	50	77
1985	9040	3099	1339	1762	1252	733	783	707	0	146	0	61	59	64
1986	9657	6076	768	1464	1277	724	599	735	0	147	0	60	50	64
1987	10965	7190	1280	1231	1391	447	659	1532	0	146	0	53	44	57
1988	11675	7334	1348	1683	1429	927	622	1592	0	145	0	47	41	49
1989	12320	8195	2586	2263	1423	1117	848	1535	0	144	0	43	54	42
1990	11919	8015	3687	2634	1374	1168	986	1232	0	143	0	40	69	34
1991	12333	9560	3118	4141	1369	2444	1135	2024	0	142	0	35	36	34
1992	12006	2160	4082	4235	1360	1685	1619	1957	0	141	0	58	19	69
1993	12928	1988	3254	3736	1396	1300	1984	3278	0	139	0	63	35	72
1994	13116	2208	4739	3768	1386	2816	1640	2623	0	138	0	63	32	72
1995	6556	3748	4546	3417	1103	3274	1432	1915	0	136	0	72	29	84
1996	5633	1356	3487	3220	1092	2527	1099	1456	0	134	0	54	37	59
1997	7526	1963	5215	4491	1130	3802	1437	2119	0	134	0	102	44	122
1998	8825	5649	4217	3977	1124	2669	1633	0	0	133	0	142	24	178
1999	7620	2376	5490	4678	1077	4178	1515	0	0	132	0	98	11	123
2000	7512	4255	4018	2170	1058	471	633	0	0	131	0	98	13	122
2001	7434	4658	2527	2273	1081	584	851	0	0	129	0	76	44	93
2002	7667	8296	1936	2526	1050	597	811	0	0	128	0	102	95	127
2003	6588	10123	1983	2458	1027	746	1127	0	0	127	0	112	38	141
2004	6037	6385	1398	2324	892	708	1172	0	12	125	0	57	48	69
2005	7244	6076	2047	2493	899	593	1204	0	80	123	0	147	109	186
2006	5841	7095	1924	2270	860	762	1209	0	83	122	0	118	81	149

Table C. 4 Catch (t) composition of reconstructed Red Sea beach seine fishery.

Years	Anchovy	Sardine	Mullets	Queenfish	Jacks	Little tuna	Others	Years	Anchovy	Sardine	Mullets	Queenfish	Jacks	Little tuna	Others
1950	18133	9023	50	100	250	0	0	1979	1102	476	41	83	207	66	33
1951	18142	9028	50	100	250	0	0	1980	1145	495	38	75	188	60	30
1952	18154	9033	50	100	250	0	0	1981	1258	544	34	68	169	54	27
1953	18166	9038	50	100	250	0	0	1982	1262	546	30	60	150	48	24
1954	18180	9044	50	100	250	0	0	1983	1266	547	26	53	131	42	21
1955	18159	9035	50	100	250	0	0	1984	1269	548	23	45	113	36	18
1956	15849	7879	50	100	250	0	0	1985	1271	549	19	38	94	30	15
1957	13539	6722	50	100	250	0	0	1986	1296	560	15	30	75	24	12
1958	11229	5566	50	100	250	0	0	1987	1312	567	11	23	56	18	9
1959	8458	4180	50	100	250	0	0	1988	1298	561	8	15	38	12	6
1960	7426	3662	50	100	250	0	0	1989	1316	569	4	8	19	6	3
1961	9716	4806	50	100	250	0	0	1990	1334	576	0	0	0	0	0
1962	7150	3522	50	100	250	0	0	1991	1409	609	0	0	0	0	0
1963	6309	3100	50	100	250	0	0	1992	1443	624	0	0	0	0	0
1964	7691	3790	50	100	250	0	0	1993	1445	624	0	0	0	0	0
1965	12644	6265	50	100	250	0	0	1994	1458	630	0	0	0	0	0
1966	14169	7026	50	100	250	0	0	1995	1567	677	0	0	0	0	0
1967	15339	377	50	100	250	80	40	1996	1581	683	0	0	0	0	0
1968	8895	384	50	100	250	80	40	1997	1571	679	0	0	0	0	0
1969	8254	4065	50	100	250	0	0	1998	1582	684	0	0	0	0	0
1970	11595	5735	50	100	250	0	0	1999	1583	684	0	0	0	0	0
1971	12136	6005	50	100	250	0	0	2000	1582	684	0	0	0	0	0
1972	8961	412	50	100	250	80	40	2001	1599	691	0	0	0	0	0
1973	3664	421	49	98	244	78	39	2002	1555	672	0	0	0	0	0
1974	4083	432	48	95	238	76	38	2003	1560	674	0	0	0	0	0
1975	2433	442	46	93	231	74	37	2004	1563	676	0	0	0	0	0
1976	1047	453	45	90	225	72	36	2005	1563	676	0	0	0	0	0
1977	1072	463	44	88	219	70	35	2006	1560	674	0	0	0	0	0
1978	1081	467	43	85	213	68	34								

Table C. 5 Catch (t) composition of reconstructed Red Sea shark fishery by countries.

Years	Eritrea	Sudan	Yemen	Egypt	Saudi Arabia	Years	Eritrea	Sudan	Yemen	Egypt	Saudi Arabia
1950	413	15	483	3	343	1979	14	68	1204	16	850
1951	413	15	490	3	343	1980	14	62	1173	13	776
1952	413	15	499	3	343	1981	14	118	1349	10	976
1953	413	15	509	4	343	1982	14	105	1474	30	976
1954	413	15	519	4	351	1983	14	0	1497	12	1030
1955	413	15	503	5	360	1984	14	42	493	14	690
1956	413	15	516	5	369	1985	14	40	1548	16	419
1957	413	15	529	6	377	1986	14	38	1133	14	436
1958	413	15	542	6	386	1987	14	36	997	12	556
1959	413	15	555	7	394	1988	14	34	747	12	600
1960	413	15	569	7	403	1989	14	33	776	15	600
1961	413	15	584	8	411	1990	14	94	690	19	556
1962	413	15	599	8	420	1991	14	106	3282	10	556
1963	413	15	614	8	429	1992	14	109	7233	5	556
1964	394	15	628	9	413	1993	14	98	7798	10	600
1965	937	15	642	9	477	1994	14	96	7756	9	600
1966	1146	15	655	10	509	1995	14	105	5352	8	310
1967	3174	15	667	10	549	1996	16	117	4265	10	308
1968	5508	15	678	11	600	1997	14	86	5645	12	348
1969	1900	15	690	11	676	1998	19	95	5220	7	347
1970	1500	17	702	12	676	1999	42	110	6187	3	489
1971	2300	18	702	12	676	2000	143	99	2075	3	471
1972	1100	19	714	13	694	2001	120	102	1327	5	516
1973	400	21	766	13	711	2002	159	97	414	4	480
1974	500	22	866	14	729	2003	135	104	762	4	457
1975	30	23	1022	14	747	2004	91	117	869	4	320
1976	100	34	1095	14	765	2005	49	127	1309	5	471
1977	14	32	1211	15	765	2006	255	146	1434	3	473
1978	14	34	1260	15	968						

Table C. 6 Catch (t) composition of reconstructed Red Sea trawl (retained) fishery.

Years	Lizardfish	Threadfin bream	Shrimp	Snappers	Cuttlefish	Emperors	Mullets	Horse Mackerel & Scad	Grunts
1950	182	31	69	47	11	0	14	16	0
1951	193	33	71	50	11	0	15	17	0
1952	204	35	74	53	12	0	16	18	0
1953	215	36	76	56	12	0	17	19	0
1954	225	38	78	58	13	0	18	20	0
1955	236	40	80	61	14	0	19	21	0
1956	123	21	56	32	7	0	10	11	0
1957	822	139	205	213	48	0	65	73	0
1958	908	167	220	230	51	0	86	79	0
1959	934	171	225	237	53	0	88	82	0
1960	626	195	134	126	28	0	147	44	1
1961	1507	511	267	287	64	0	401	99	2
1962	2587	757	477	541	121	0	556	187	3
1963	3622	966	686	796	178	0	676	275	3
1964	4506	1053	896	1050	235	0	676	363	3
1965	4664	1078	930	1091	244	0	687	377	3
1966	3129	829	599	690	154	0	577	238	3
1967	2897	779	553	634	142	0	547	219	3
1968	2711	766	507	578	129	0	553	200	3
1969	2551	774	461	522	117	0	580	180	3
1970	2280	693	1380	467	105	0	519	161	3
1971	2058	632	1286	419	94	0	476	145	3
1972	2677	721	1166	585	131	0	507	202	3
1973	1522	462	608	312	70	0	346	108	2
1974	1666	408	562	381	85	0	271	131	1
1975	3555	713	881	876	196	0	403	303	1
1976	3461	694	887	852	191	0	391	294	1
1977	2839	507	822	725	162	0	253	250	0
1978	2593	444	912	668	150	0	209	231	0

Years	Lizardfish	Threadfin bream	Shrimp	Snappers	Cuttlefish	Emperors	Mullets	Horse Mackerel & Scad	Grunts
1979	2224	397	497	566	127	0	196	196	0
1980	2298	501	604	699	126	0	178	215	0
1981	2879	430	646	621	184	0	168	284	0
1982	2443	389	824	630	180	63	288	164	17
1983	2141	418	953	530	239	131	134	203	36
1984	1085	397	1319	564	380	193	101	323	53
1985	1302	416	1255	568	377	261	117	232	73
1986	2782	408	1117	538	415	329	180	243	91
1987	1917	325	1097	508	535	406	206	261	113
1988	1033	253	1443	679	349	291	285	235	81
1989	839	289	1141	1117	481	429	269	170	119
1990	640	235	1281	966	457	365	259	160	101
1991	927	252	1848	708	476	405	323	207	112
1992	1261	316	1228	862	575	486	516	102	135
1993	1409	628	1381	952	681	554	423	161	133
1994	2821	1308	2082	805	813	718	357	291	282
1995	4287	1891	2847	676	752	798	397	143	337
1996	3567	1718	2526	687	787	1461	316	148	500
1997	4345	2287	2761	674	943	972	329	290	175
1998	4845	2661	2390	712	970	949	264	273	188
1999	7636	4752	2279	915	1152	1199	287	160	708
2000	9574	5109	2510	1064	1285	1383	296	189	1121
2001	9962	4959	2825	1065	1386	1367	336	278	552
2002	12571	5408	2142	1141	1098	1326	428	241	480
2003	10014	4824	3488	1226	1924	1225	487	260	261
2004	10885	4256	2112	1058	3474	927	458	82	383
2005	8314	3604	2209	904	3028	992	469	148	246
2006	7905	3221	2036	609	2720	949	392	355	560

Table C.6 continued.

Years	Jacks	Catfish	Barracuda	Crab	Indian mackerel	Leopard flounder	Goat fish	Sole	Others
1950	0	0	0	0	0	0	0	0	0
1951	0	0	0	0	0	0	0	0	0
1952	0	0	0	0	0	0	0	0	0
1953	0	0	0	0	0	0	0	0	0
1954	0	0	0	0	0	0	0	0	0
1955	0	0	0	0	0	0	0	0	0
1956	0	0	0	0	0	0	0	0	0
1957	0	0	0	0	0	0	0	0	0
1958	0	0	1	0	0	0	0	0	1
1959	0	0	1	0	0	0	0	0	1
1960	0	0	6	0	0	0	0	1	9
1961	0	0	17	0	0	0	0	3	26
1962	0	0	22	0	0	0	0	4	32
1963	0	0	24	0	0	0	0	4	35
1964	0	0	20	0	0	0	0	4	29
1965	0	0	20	0	0	0	0	4	29
1966	0	0	20	0	0	0	0	4	30
1967	0	0	20	0	0	0	0	4	29
1968	0	0	21	0	0	0	0	4	31
1969	0	0	23	0	0	0	0	4	34
1970	0	0	21	0	0	0	0	4	31
1971	0	0	19	0	0	0	0	4	29
1972	0	0	18	0	0	0	0	3	27
1973	0	0	14	0	0	0	0	3	21
1974	0	0	9	0	0	0	0	2	13
1975	0	0	8	0	0	0	0	1	11
1976	0	0	7	0	0	0	1	1	11
1977	0	0	2	0	0	0	0	0	3
1978	0	0	0	0	0	0	1	0	0
1979	0	0	1	0	0	0	1	0	2

Years	Jacks	Catfish	Barracuda	Crab	Indian mackerel	Leopard flounder	Goat fish	Sole	Others
1980	0	0	1	0	0	0	0	0	2
1981	0	0	0	0	0	0	1	0	0
1982	0	21	0	30	0	0	4	0	0
1983	0	44	0	62	0	0	4	0	0
1984	0	64	0	91	0	0	4	0	0
1985	0	87	0	123	0	0	7	0	0
1986	0	110	0	155	0	0	10	0	0
1987	0	136	0	191	0	0	13	0	0
1988	0	97	0	137	0	0	16	0	0
1989	0	144	0	202	0	0	19	0	0
1990	0	122	0	172	0	0	22	0	0
1991	0	135	0	190	0	0	6	0	0
1992	0	163	0	229	0	0	6	0	0
1993	0	160	0	233	0	0	6	0	0
1994	213	258	181	249	26	22	6	0	267
1995	306	290	260	244	38	32	6	0	383
1996	804	169	174	257	58	0	6	0	244
1997	1	197	3	317	0	0	6	0	3
1998	114	316	27	288	0	1	12	0	118
1999	344	335	118	269	20	23	18	0	375
2000	1876	954	604	290	196	119	19	0	1219
2001	901	547	432	300	99	126	19	0	1374
2002	603	319	328	289	13	69	20	0	611
2003	270	284	1869	320	5	53	23	0	682
2004	172	322	360	190	6	73	63	0	435
2005	97	154	191	310	4	20	60	0	334
2006	266	403	570	244	269	85	60	0	1438

Table C. 7 Catch (t) composition of reconstructed Red Sea trawl (discard) fishery.

Years	Pony Fish	Gaper	Flounder	Crab	Tigerfish	Sand dollars	Cutlassfish	Mojarra	Sponge	Jacks	Flatheads	Puffers
1950	675	296	118	82	9	79	5	5	47	46	3	3
1951	693	305	122	84	9	81	5	5	49	46	3	3
1952	710	313	125	86	9	83	5	5	50	46	3	3
1953	725	321	128	88	9	86	5	5	51	46	3	3
1954	739	328	131	90	9	87	5	5	52	46	3	3
1955	753	335	134	92	9	89	5	5	54	46	3	3
1956	424	170	68	48	9	45	5	5	27	46	3	3
1957	2294	1105	442	297	9	295	5	5	177	46	3	3
1958	2529	1165	466	317	22	311	13	13	186	6	6	6
1959	2538	1169	468	318	22	312	13	13	187	6	6	6
1960	1579	609	244	174	41	162	23	23	97	12	12	12
1961	3422	1351	541	384	81	360	46	46	216	23	23	23
1962	5829	2488	995	691	96	663	55	55	398	28	28	28
1963	8067	3571	1428	982	105	952	60	60	571	30	30	30
1964	9996	4602	1841	1253	89	1227	51	51	736	26	26	26
1965	10136	4674	1870	1272	89	1247	51	51	748	25	25	25
1966	6584	2886	1154	796	92	770	52	52	462	26	26	26
1967	5975	2593	1037	717	89	692	51	51	415	25	25	25
1968	5454	2313	925	643	94	617	53	53	370	27	27	27
1969	4992	2044	817	574	102	545	58	58	327	29	29	29
1970	5298	1786	714	532	195	476	111	111	286	519	56	56
1971	4751	1567	627	470	183	418	104	104	251	490	52	52
1972	5624	2144	857	615	151	572	86	86	343	359	43	43
1973	3118	1117	447	326	100	298	57	57	179	185	29	29
1974	3283	1336	534	376	69	356	39	39	214	127	20	20
1975	6508	3010	1204	818	55	803	31	31	482	82	16	16
1976	6287	2867	1147	782	63	764	36	36	459	90	18	18
1977	5117	2389	956	648	38	637	22	22	382	111	11	11
1978	4793	2158	863	591	54	575	31	31	345	174	15	15
1979	3774	1791	716	484	22	478	12	12	287	6	6	6

Years	Pony Fish	Gaper	Flounder	Crab	Tigerfish	Sand dollars	Cutlassfish	Mojarra	Sponge	Jacks	Flatheads	Puffers
1980	4125	2033	813	544	7	542	4	4	325	2	2	2
1981	4445	2158	863	580	15	575	8	8	345	4	4	4
1982	5154	1706	682	511	197	455	112	112	273	56	56	56
1983	4923	1610	644	484	192	429	110	110	258	55	55	55
1984	4648	1339	536	421	222	357	127	127	214	64	64	64
1985	4502	1274	510	403	221	340	126	126	204	63	63	63
1986	5382	1699	679	517	224	453	128	128	272	64	64	64
1987	4484	1429	572	433	184	381	105	105	229	52	52	52
1988	5605	1227	491	429	356	327	203	203	196	102	102	102
1989	4361	1237	495	391	213	330	122	122	198	61	61	61
1990	4145	1018	407	340	238	272	136	136	163	68	68	68
1991	6026	1044	417	405	445	278	254	254	167	127	127	127
1992	4704	1324	529	419	232	353	133	133	212	66	66	66
1993	5981	1140	456	423	418	304	239	239	182	119	119	119
1994	10336	937	375	523	955	250	546	546	150	273	273	273
1995	15352	1023	409	702	1502	273	858	858	164	429	429	429
1996	14825	969	388	674	1455	258	831	831	155	416	416	416
1997	16482	1039	416	742	1626	277	929	929	166	465	465	465
1998	16799	844	338	713	1706	225	975	975	135	487	487	487
1999	19449	866	347	803	2000	231	1143	1143	139	572	572	572
2000	21111	770	308	837	2210	205	1263	1263	123	631	631	631
2001	22727	873	349	910	2369	233	1354	1354	140	677	677	677
2002	24466	1030	412	997	2530	275	1446	1446	165	723	723	723
2003	26387	1109	444	1075	2729	296	1559	1559	177	780	780	780
2004	21720	1017	407	906	2223	271	1270	1270	163	635	635	635
2005	18859	1039	416	818	1895	277	1083	1083	166	541	541	541
2006	16437	885	354	709	1656	236	946	946	142	473	473	473

Table C.7 continued.

Years	Soles	Goatfish	Mantis shrimp	Lizard fish	Threadfin Bream	Grunt	Catfish	Barracudas	Cuttlefish	Others
1950	3	1	1	38	32	12	8	3	1	12
1951	3	1	1	38	32	12	8	3	1	12
1952	3	1	1	38	32	12	8	3	1	12
1953	3	1	1	38	32	12	8	3	1	12
1954	3	1	1	38	32	12	8	3	1	12
1955	3	1	1	38	32	12	8	3	1	12
1956	3	1	1	38	32	12	8	3	1	12
1957	3	1	1	38	32	12	8	3	1	12
1958	6	3	3	0	0	0	0	0	0	29
1959	6	3	3	0	0	0	0	0	0	29
1960	12	6	6	0	0	0	0	0	0	52
1961	23	12	12	0	0	0	0	0	0	104
1962	28	14	14	0	0	0	0	0	0	124
1963	30	15	15	0	0	0	0	0	0	134
1964	26	13	13	0	0	0	0	0	0	115
1965	25	13	13	0	0	0	0	0	0	114
1966	26	13	13	0	0	0	0	0	0	118
1967	25	13	13	0	0	0	0	0	0	114
1968	27	13	13	0	0	0	0	0	0	120
1969	29	15	15	0	0	0	0	0	0	131
1970	56	28	28	405	347	130	87	29	14	251
1971	52	26	26	383	328	123	82	27	14	235
1972	43	22	22	276	237	89	59	20	10	194
1973	29	14	14	137	117	44	29	10	5	128
1974	20	10	10	94	81	30	20	7	3	89
1975	16	8	8	58	49	19	12	4	2	71
1976	18	9	9	63	54	20	13	4	2	80
1977	11	5	5	88	75	28	19	6	3	49
1978	15	8	8	139	119	45	30	10	5	69
1979	6	3	3	0	0	0	0	0	0	28

Years	Soles	Goatfish	Mantis shrimp	Lizard fish	Threadfin Bream	Grunt	Catfish	Barracudas	Cuttlefish	Others
1980	2	1	1	0	0	0	0	0	0	8
1981	4	2	2	0	0	0	0	0	0	19
1982	56	28	28	0	0	0	0	0	0	253
1983	55	27	27	0	0	0	0	0	0	247
1984	64	32	32	0	0	0	0	0	0	286
1985	63	32	32	0	0	0	0	0	0	284
1986	64	32	32	0	0	0	0	0	0	288
1987	52	26	26	0	0	0	0	0	0	236
1988	102	51	51	0	0	0	0	0	0	457
1989	61	30	30	0	0	0	0	0	0	274
1990	68	34	34	0	0	0	0	0	0	306
1991	127	64	64	0	0	0	0	0	0	572
1992	66	33	33	0	0	0	0	0	0	299
1993	119	60	60	0	0	0	0	0	0	537
1994	273	136	136	0	0	0	0	0	0	1228
1995	429	215	215	0	0	0	0	0	0	1931
1996	416	208	208	0	0	0	0	0	0	1871
1997	465	232	232	0	0	0	0	0	0	2091
1998	487	244	244	0	0	0	0	0	0	2193
1999	572	286	286	0	0	0	0	0	0	2572
2000	631	316	316	0	0	0	0	0	0	2841
2001	677	338	338	0	0	0	0	0	0	3046
2002	723	361	361	0	0	0	0	0	0	3252
2003	780	390	390	0	0	0	0	0	0	3508
2004	635	318	318	0	0	0	0	0	0	2858
2005	541	271	271	0	0	0	0	0	0	2436
2006	473	237	237	0	0	0	0	0	0	2129

Table C. 8 Catch (t) composition of reconstructed Red Sea purse seine fishery.

Years	Horse mackerel & scads	Round herring	Goldstripe sardinella	Indian mackerel	Slimy mackerel	Spotted sardinella	Barracudas	Kingfish	Queenfish	Others
1950	0	0	122	0	0	0	0	0	0	11
1951	0	0	122	0	0	0	0	0	0	11
1952	0	0	122	0	0	0	0	0	0	11
1953	0	0	122	0	0	0	0	0	0	11
1954	0	0	122	0	0	0	0	0	0	11
1955	0	0	122	0	0	0	0	0	0	11
1956	0	0	122	0	0	0	0	0	0	11
1957	0	0	122	0	0	0	0	0	0	11
1958	0	0	122	0	0	0	0	0	0	11
1959	0	0	122	0	0	0	0	0	0	11
1960	0	0	2438	0	0	0	0	0	0	212
1961	0	0	4046	0	0	0	0	0	0	352
1962	0	0	7502	0	0	0	0	0	0	652
1963	0	0	6943	0	0	0	0	0	0	604
1964	0	0	2322	0	0	1	0	0	0	1136
1965	0	0	1955	0	0	1	0	0	0	957
1966	0	0	2429	0	0	2	0	0	0	1189
1967	2400	1163	524	341	0	629	0	0	0	183
1968	3142	1523	686	446	0	823	0	0	0	240
1969	3884	1883	848	551	0	1018	0	0	0	297
1970	4627	2243	1010	657	0	1212	0	0	0	354
1971	5968	2893	1303	847	0	1564	0	0	0	456
1972	5476	2654	1196	777	0	1435	0	0	0	418
1973	1221	592	267	173	0	320	0	0	0	93
1974	6572	3186	1435	933	0	1722	0	0	0	502
1975	4388	2127	958	623	0	1150	0	0	0	335
1976	8522	4131	1861	1209	0	2233	0	0	0	651
1977	6930	3359	1513	983	0	1816	0	0	0	530
1978	6606	3202	1442	938	0	1731	0	0	0	505

Years	Horse mackerel & scads	Round herring	Goldstripe sardinella	Indian mackerel	Slimy mackerel	Spotted sardinella	Barracudas	Kingfish	Queenfish	Others
1979	9324	4519	2036	1323	0	2443	0	0	0	713
1980	6294	3051	1374	893	0	1649	0	0	0	481
1981	5461	2647	1192	775	0	1431	0	0	0	417
1982	7328	3489	1572	1193	0	1886	33	21	16	550
1983	11856	6133	796	948	2331	956	69	43	34	932
1984	13531	6952	903	1194	2642	1083	101	64	50	1056
1985	9721	4860	631	1181	1847	757	137	86	68	738
1986	8046	3900	506	1273	1482	608	173	109	85	592
1987	9626	4652	604	1556	1768	725	213	134	105	707
1988	11700	5875	763	1359	2233	916	153	96	75	893
1989	16385	8205	1065	1960	3118	1279	226	142	111	1246
1990	16450	8309	1079	1796	3158	1295	192	121	94	1262
1991	14102	7023	912	1780	2669	1094	213	134	105	1067
1992	14338	7058	917	2007	2683	1100	256	161	126	1072
1993	17635	8813	1144	2153	3349	1373	251	158	124	1339
1994	10622	5081	660	1841	1931	792	260	164	128	772
1995	10641	5120	665	1773	1946	798	247	155	121	778
1996	9157	4322	561	1728	1643	674	253	159	124	657
1997	10293	4803	624	2074	1826	749	310	195	153	730
1998	8411	4036	524	2197	1534	629	269	170	132	613
1999	6551	3180	413	2644	1209	496	222	173	111	483
2000	11205	5629	731	3001	2139	877	234	182	117	855
2001	8296	4088	531	2857	1554	637	234	183	117	621
2002	9216	4579	821	2836	1740	939	243	203	114	696
2003	8602	4255	935	2761	1617	1045	249	217	112	646
2004	8976	4585	1252	3414	1743	1372	219	254	90	697
2005	4999	2444	695	2989	929	758	341	255	104	371
2006	5160	2464	698	2987	937	762	321	161	181	374

Appendix D Supplementary material for Chapter 5

Table D. 1 Summary of the major influences on the incentives to misreport, arrows indicate whether the influence increases or decreases the incentive.

		Influence					
Period	Event summary	Small pelagic	Finfish trawl	Shrimp	Rational	Duration	Ref.*
50-54	Growing operation of small pelagic fishery	↑			Increasing effort	50 - 54	1
	Shrimp fishery trial			↑	New operation	50 - 54	1
55 - 59	Small pelagic fishery at its highest peak	↑			High effort	55	2
	First off shore survey to locate trawling grounds by Israeli		↑		New grounds	57 - 58	3
	First commercial trawl report available		↑	↑	Start of operation	58	3
60 - 64	Sea Fisheries advisory board of Massawa established	↑	↑	↑	Encouraged investment	60	1
	Yemenite fishermen who were expertise stopped from operation	↓			Less effort	60	3
	Israeli expert working as advisory in the Eritrean Red Sea	↑	↑	↑	Resource knowledge	60 - 63	3
	Experimental inshore shrimp fishery in central and southern part			↑	New grounds	60 - 63	3
	Purse seine survey	↑			New grounds	62	4
	Carrier ship to Israel stopped operating, trawlers had to do it themselves		↓	↓	Less effective effort	63 - 65	3
	Some trawlers stopped operation		↓	↓	Less effort	63	3
	First phase of motorization of Dhows for Beach seine	↑			Increased catching power	63	1
	Freedom from hunger campaign	↑	↑	↑	Increased demand	60 - 63	3
65 - 69	Yemenite fishermen resume operation again	↑			More effort	65	3
	Master plan for the development of fishery	↑	↑	↑	Cleared way for investment	65	5
	Israeli expert working as advisory in the Eritrean Red Sea	↑	↑	↑	Resource knowledge	66 - 69	1

		Influence					
		Small	Finfish				
Period	Event summary	pelagic	trawl	Shrimp	Rational	Duration	Ref.*
	More boat motorization	↑			Increased catching power	66	1
	Training of fishermen to use new technology	↑	↑	↑	Technical knowledge	66	1
	Closer of Suez Canal due to middle east war	↓			Market	67	1
	Synthetic fibers and outboard engines in small Beach seine boats	↑			Increased catching power	67 - 04	1
	Tickler chain introduced in Shrimp trawlers			↑	Increased catching power	67 – 04	1
	Trial of 57' semi-balloon shrimp trawl			↑	Increased catching power	68	1
	Experiment of different size and types shrimp trawls			↑	Increased catching power	68	1
	More trawlers added		↑		More effort	68	1
	Less demand for Lizard fish in the market		↑	↑	Market and grading	68	1
	Tendency to use trawl trash for fish meal		↓	↓	Retained and reported	66 - 69	1
	Minimum mesh size of 50 mm at the cod end adopted		↓	↓	Regulation	66 - 69	1
	Campaign to increase fish consumption locally	↑	↑	↑	Increased demand	66 - 69	1
	Resumption of fishmeal export, because of alternative market	↑			Market	69 -71	6
70 - 74	General political instability in the country	↓	↓	↓	Instability	72	7
75 - 79	Major war in the coastal area	↓	↓	↓	Instability	77	
	Fishing industry totally collapsed	↓	↓	↓	Less effort	78	7
80 - 84	Little recovery of the fishing industry	↑	↑	↑	More effort	83 - 90	7
	Resource survey	↑	↑	↑	Resource knowledge	84	8
85 - 89	Establishment of marine and fisheries institute	↑	↑	↑	Resource knowledge	86 - 90	4

		Influence					
		Small	Finfish				
Period	Event summary	pelagic	trawl	Shrimp	Rational	Duration	Ref.*
90 - 94	Major war in the coastal area	↓	↓	↓	Instability	90	
	Independence of Eritrea	↑	↑	↑	Resumption of operation	91	
	Formation of Ministry of Marine Resources (later Ministry of Fisheries)	↑	↑	↑	Encouraged investment	91	
	Log book and onboard observers introduced	↓	↓	↓	Better reporting	92	
	Foreign trawlers legally operating in Eritrea		↑	↑	More effort	94 - 97	9
	Log book system improved and database system working	↓	↓	↓	Better reporting	96	10
	Infrastructure development projects	↑	↑	↑	Encouraged investment	92	11
95 - 99	Resource survey	↑	↑	↑	Resource knowledge	97	13
	Foreign trawlers stopped operation		↓	↓	Less effort	97 - 98	12
	Fisheries proclamation	↓	↓	↓	Regulation	98	14
	Political instability	↓	↓	↓	Instability	98	
	Restarting of trawlers		↑		More effort	99	15
	Commencement of large scale shrimp fishery			↑	More effort	99	16
	Fish processing plants established		↑		Increased market	99	16
	A good shrimp ground found		↓		Cleaner catch	99	16

		Influence					
		Small	Finfish				
Period	Event summary	pelagic	trawl	Shrimp	Rational	Duration	Ref.*
00 - 04	War in the southern part of the coast	↓	↓	↓	Instability	00	
	Existing trawlers increased their effort after the war, mainly in the north		↑		More effort	00	16
	New medium sized (11 – 18 m) shrimp trawlers operating			↑	More effort	00	16
	New trawlers added		↑	↑	More effort	00	16
	New trawlers added		↑	↑	More effort	04	17

*1 Grofit (1971) 2 Jonson (1956) 3 Ben-Yami (1964) 4 Melake (1988) 5 Atkins (1965)
6 Ben-Yami (1975) 7 Giudicelli (1984) 8 Blindheim (1984) 9 Hartmann (1997) 10 MOF (1996)
11 FAO (1993) 12 Tesfamichael and Zeremariam (1998) 13 Antoine *et al.,* (1997) 14 MOF (1998)
15 Habteselassie and Habte (2000) 16 Gebremichael *et al.,* (2001) 17 Shaebia.org (2005)

Appendix E Supplementary material for Chapter 6

E.1 Ecopath input data

Table E. 1 Fish species included in the Red Sea model grouped by functional groups.

Group	Family	Scientific name	FishBase Code	FishBase common name
Whale shark	Rhincodontidae	*Rhincodon typus*	2081	Whale shark
Rays	Myliobatidae	*Aetobatus flagellum*	8973	Longheaded eagle ray
	Myliobatidae	*Aetobatus narinari*	1250	Spotted eagle ray
	Myliobatidae	*Aetobatus ocellatus*	12600	
	Dasyatidae	*Dasyatis bennetti*	15387	Bennett's stingray
	Dasyatidae	*Dasyatis kuhlii*	4508	Bluespotted stingray
	Dasyatidae	*Himantura gerrardi*	15483	Sharpnose stingray
	Dasyatidae	*Himantura imbricata*	13150	Scaly whipray
	Dasyatidae	*Himantura uarnak*	5507	Honeycomb stingray
	Myliobatidae	*Manta ehrenbergii*	54614	
	Myliobatidae	*Mobula thurstoni*	2588	Smooth-tail mobula
	Dasyatidae	*Pastinachus sephen*	8203	Cowtail stingray
	Dasyatidae	*Taeniura lymma*	5399	Bluespotted ribbontail ray
	Dasyatidae	*Taeniura meyeni*	6482	Blotched fantail ray
	Torpedinidae	*Torpedo panthera*	27060	Panther electric ray
	Torpedinidae	*Torpedo sinuspersici*	7970	Marbled electric ray
	Torpedinidae	*Torpedo suessii*	61378	
	Dasyatidae	*Urogymnus asperrimus*	5400	Porcupine ray
Reef top predators	Belonidae	*Ablennes hians*	972	Flat needlefish
	Serranidae	*Aethaloperca rogaa*	6441	Redmouth grouper
	Carangidae	*Alectis indicus*	10	Indian threadfish
	Antennariidae	*Antennarius coccineus*	5402	Scarlet frogfish
	Antennariidae	*Antennarius commerson*	7293	Commerson's frogfish
	Antennariidae	*Antennarius hispidus*	8074	Shaggy angler
	Antennariidae	*Antennarius nummifer*	5403	Spotfin frogfish
	Antennariidae	*Antennarius pictus*	10276	Painted frogfish
	Antennariidae	*Antennarius striatus*	5474	Striated frogfish
	Lutjanidae	*Aphareus furca*	81	Small toothed jobfish
	Lutjanidae	*Aphareus rutilans*	83	Rusty jobfish
	Lutjanidae	*Aprion virescens*	84	Green jobfish
	Carangidae	*Atule mate*	1893	Yellowtail scad
	Bothidae	*Bothus mancus*	7641	Flowery flounder
	Ophichthidae	*Brachysomophis cirrocheilos*	12886	Stargazer snake eel
	Carangidae	*Carangoides bajad*	1923	Orangespotted trevally
	Carangidae	*Carangoides chrysophrys*	4441	Longnose trevally
	Carangidae	*Carangoides coeruleopinnatus*	1924	Coastal trevally
	Carangidae	*Carangoides dinema*	1925	Shadow trevally
	Carangidae	*Carangoides fulvoguttatus*	1926	Yellowspotted trevally
	Carangidae	*Carangoides gymnostethus*	1905	Bludger
	Carangidae	*Carangoides malabaricus*	4443	Malabar trevally

Group	Family	Scientific name	FishBase Code	FishBase common name
	Carangidae	*Carangoides orthogrammus*	1909	Island trevally
	Carangidae	*Carangoides plagiotaenia*	1910	Barcheek trevally
	Carangidae	*Caranx ignobilis*	1895	Giant trevally
	Carangidae	*Caranx melampygus*	1906	Bluefin trevally
	Carangidae	*Caranx sexfasciatus*	1917	Bigeye trevally
	Odontaspididae	*Carcharias taurus*	747	Sand tiger shark
	Serranidae	*Cephalopholis argus*	6396	Peacock hind
	Serranidae	*Cephalopholis boenak*	6444	Chocolate hind
	Serranidae	*Cephalopholis hemistiktos*	6447	Yellowfin hind
	Serranidae	*Cephalopholis miniata*	6450	Coral hind
	Serranidae	*Cephalopholis oligosticta*	6451	Vermilion hind
	Serranidae	*Cephalopholis sexmaculata*	6453	Sixblotch hind
	Labridae	*Cheilinus undulatus*	5604	Humphead wrasse
	Labridae	*Cheilio inermis*	5623	Cigar wrasse
	Apogonidae	*Cheilodipterus macrodon*	5781	Large toothed cardinalfish
	Chirocentridae	*Chirocentrus dorab*	6358	Dorab wolf-herring
	Congridae	*Conger cinereus*	6654	Longfin African conger
	Serranidae	*Diploprion drachi*	24437	Yellowfin soapfish
	Muraenidae	*Echidna nebulosa*	5388	Snowflake moray
	Serranidae	*Epinephelus coeruleopunctatus*	6440	Whitespotted grouper
	Serranidae	*Epinephelus fuscoguttatus*	4460	Brown-marbled grouper
	Serranidae	*Epinephelus hexagonatus*	6660	Starspotted grouper
	Serranidae	*Epinephelus lanceolatus*	6468	Giant grouper
	Serranidae	*Epinephelus malabaricus*	6439	Malabar grouper
	Serranidae	*Epinephelus polyphekadion*	6473	Camouflage grouper
	Serranidae	*Epinephelus tukula*	5525	Potato grouper
	Fistulariidae	*Fistularia commersonii*	5444	Bluespotted cornetfish
	Fistulariidae	*Fistularia petimba*	3276	Red cornetfish
	Scombridae	*Grammatorcynus bilineatus*	104	Double-lined mackerel
	Scombridae	*Gymnosarda unicolor*	106	Dogtooth tuna
	Muraenidae	*Gymnothorax elegans*	23130	Elegant moray
	Muraenidae	*Gymnothorax favagineus*	5391	Laced moray
	Muraenidae	*Gymnothorax flavimarginatus*	5392	Yellow-edged moray
	Muraenidae	*Gymnothorax griseus*	8058	Geometric moray
	Muraenidae	*Gymnothorax meleagris*	5394	Turkey moray
	Muraenidae	*Gymnothorax moluccensis*	27334	Moluccan moray
	Muraenidae	*Gymnothorax nudivomer*	7465	Starry moray
	Muraenidae	*Gymnothorax pictus*	6395	Peppered moray
	Muraenidae	*Gymnothorax punctatofasciatus*	27341	
	Muraenidae	*Gymnothorax punctatus*	27325	Red Sea whitespotted moray
	Muraenidae	*Gymnothorax rueppellii*	5396	Banded moray
	Muraenidae	*Gymnothorax undulatus*	4905	Undulated moray
	Antennariidae	*Histrio histrio*	3089	Sargassumfish
	Labridae	*Hologymnosus annulatus*	5637	Ring wrasse
	Lethrinidae	*Lethrinus lentjan*	1863	Pink ear emperor
	Lethrinidae	*Lethrinus olivaceus*	1864	Longface emperor
	Lutjanidae	*Lutjanus ehrenbergii*	793	Blackspot snapper

Group	Family	Scientific name	FishBase Code	FishBase common name
	Lutjanidae	*Lutjanus erythropterus*	1406	Crimson snapper
	Lutjanidae	*Lutjanus fulvus*	262	Blacktail snapper
	Lutjanidae	*Lutjanus johnii*	264	John's snapper
	Lutjanidae	*Lutjanus lemniscatus*	157	Yellowstreaked snapper
	Lutjanidae	*Lutjanus malabaricus*	162	Malabar blood snapper
	Lutjanidae	*Lutjanus monostigma*	166	Onespot snapper
	Lutjanidae	*Lutjanus quinquelineatus*	172	Five-lined snapper
	Lutjanidae	*Lutjanus rivulatus*	173	Blubberlip snapper
	Lutjanidae	*Lutjanus russellii*	176	Russell's snapper
	Lutjanidae	*Lutjanus sanguineus*	177	Humphead snapper
	Lutjanidae	*Lutjanus sebae*	178	Emperor red snapper
	Lutjanidae	*Macolor niger*	187	Black and white snapper
	Carangidae	*Megalaspis cordyla*	384	Torpedo scad
	Cirrhitidae	*Paracirrhites forsteri*	5952	Blackside hawkfish
	Mullidae	*Parupeneus cyclostomus*	5990	Goldsaddle goatfish
	Mullidae	*Parupeneus heptacanthus*	5991	Cinnabar goatfish
	Ephippidae	*Platax teira*	5739	Tiera batfish
	Haemulidae	*Plectorhinchus flavomaculatus*	7625	Lemon sweetlip
	Haemulidae	*Plectorhinchus gaterinus*	7703	Blackspotted rubberlip
	Haemulidae	*Plectorhinchus gibbosus*	6366	Harry hotlips
	Haemulidae	*Plectorhinchus harrawayi*	52851	
	Haemulidae	*Plectorhinchus sordidus*	7626	Sordid rubberlip
	Serranidae	*Plectropomus areolatus*	6082	Squaretail coralgrouper
	Haemulidae	*Pomadasys maculatus*	4447	Saddle grunt
	Haemulidae	*Pomadasys stridens*	7708	Striped piggy
	Priacanthidae	*Priacanthus blochii*	9903	Paeony bulleye
	Priacanthidae	*Pristigenys niphonia*	7905	Japanese bigeye
	Scorpaenidae	*Pterois volitans*	5195	Red lionfish
	Holocentridae	*Sargocentron macrosquamis*	23251	Bigscale squirrelfish
	Holocentridae	*Sargocentron melanospilos*	5345	Blackblotch squirrelfish
	Synodontidae	*Saurida gracilis*	4534	Gracile lizardfish
	Carangidae	*Scomberoides lysan*	1951	Doublespotted queenfish
	Carangidae	*Scomberoides tol*	1953	Needlescaled queenfish
	Scorpaenidae	*Scorpaenopsis barbata*	12767	Bearded scorpionfish
	Scorpaenidae	*Scorpaenopsis diabolus*	4921	False stonefish
	Scorpaenidae	*Scorpaenopsis gibbosa*	7918	Humpback scorpionfish
	Carangidae	*Selar crumenophthalmus*	387	Bigeye scad
	Carangidae	*Seriola dumerili*	1005	Greater amberjack
	Carangidae	*Seriolina nigrofasciata*	1962	Blackbanded trevally
	Sphyraenidae	*Sphyraena barracuda*	1235	Great barracuda
	Sphyraenidae	*Sphyraena flavicauda*	7937	Yellowtail barracuda
	Sphyraenidae	*Sphyraena forsteri*	5734	Bigeye barracuda
	Sphyraenidae	*Sphyraena jello*	4827	Pickhandle barracuda
	Sphyraenidae	*Sphyraena obtusata*	4493	Obtuse barracuda
	Sphyraenidae	*Sphyraena putnamae*	7938	Sawtooth barracuda
	Sphyraenidae	*Sphyraena qenie*	7939	Blackfin barracuda
	Muraenidae	*Strophidon sathete*	8595	Slender giant moray
	Synanceiidae	*Synanceia verrucosa*	5825	Stonefish
	Synodontidae	*Synodus variegatus*	5398	Variegated lizardfish
	Synodontidae	*Trachinocephalus myops*	2724	Snakefish
	Ephippidae	*Tripterodon orbis*	7694	African spadefish

Group	Family	Scientific name	FishBase Code	FishBase common name
	Belonidae	*Tylosurus acus melanotus*	1317	Keel-jawed needle fish
	Belonidae	*Tylosurus crocodilus crocodilus*	977	Hound needlefish
Large reef carnivores	Balistidae	*Abalistes stellaris*	9	Starry triggerfish
	Balistidae	*Abalistes stellatus*	58334	
	Albulidae	*Albula glossodonta*	11512	Roundjaw bonefish
	Albulidae	*Albula vulpes*	228	Bonefish
	Carangidae	*Alectis ciliaris*	988	African pompano
	Monacanthidae	*Aluterus monoceros*	4274	Unicorn leatherjacket
	Serranidae	*Anyperodon leucogrammicus*	4922	Slender grouper
	Tetraodontidae	*Arothron hispidus*	5425	White-spotted puffer
	Tetraodontidae	*Arothron stellatus*	6526	Starry toadfish
	Balistidae	*Balistoides viridescens*	6026	Titan triggerfish
	Ophidiidae	*Brotula multibarbata*	7297	Goatsbeard brotula
	Ophichthidae	*Callechelys catostoma*	12888	Black-striped snake eel
	Ophichthidae	*Callechelys marmorata*	12889	Marbled snake eel
	Balistidae	*Canthidermis maculata*	4278	Spotted oceanic triggerfish
	Carangidae	*Carangoides ferdau*	1921	Blue trevally
	Labridae	*Cheilinus fasciatus*	5600	Redbreast wrasse
	Labridae	*Cheilinus lunulatus*	12780	Broomtail wrasse
	Sparidae	*Cheimerius nufar*	444	Santer seabream
	Platycephalidae	*Cociella crocodila*	7895	Crocodile flathead
	Labridae	*Coris aygula*	5624	Clown coris
	Labridae	*Coris formosa*	7736	Queen coris
	Haemulidae	*Diagramma pictum*	4465	Painted sweetlips
	Diodontidae	*Diodon holocanthus*	4659	Long-spine porcupinefish
	Diodontidae	*Diodon hystrix*	1022	Spot-fin porcupinefish
	Diodontidae	*Diodon liturosus*	6552	Black-blotched porcupinefish
	Drepaneidae	*Drepane longimana*	7692	Concertina fish
	Echeneidae	*Echeneis naucrates*	2467	Live sharksucker
	Muraenidae	*Echidna polyzona*	5389	Barred moray
	Carangidae	*Elagatis bipinnulata*	412	Rainbow runner
	Labridae	*Epibulus insidiator*	5606	Slingjaw wrasse
	Serranidae	*Epinephelus coioides*	6465	Orange-spotted grouper
	Serranidae	*Epinephelus fasciatus*	5348	Blacktip grouper
	Serranidae	*Epinephelus morrhua*	5353	Comet grouper
	Carangidae	*Gnathanodon speciosus*	4464	Golden trevally
	Lethrinidae	*Gymnocranius grandoculis*	1834	Blue-lined large-eye bream
	Muraenidae	*Gymnomuraena zebra*	7880	Zebra moray
	Muraenidae	*Gymnothorax hepaticus*	6498	Liver-colored moray eel
	Muraenidae	*Gymnothorax javanicus*	6380	Giant moray
	Muraenidae	*Gymnothorax monochrous*	7285	Drab moray
	Labridae	*Hemigymnus fasciatus*	5635	Barred thicklip
	Labridae	*Hemigymnus melapterus*	5636	Blackeye thicklip
	Priacanthidae	*Heteropriacanthus cruentatus*	1150	Glasseye
	Kuhliidae	*Kuhlia mugil*	5790	Barred flagtail
	Kyphosidae	*Kyphosus cinerascens*	5805	Blue seachub
	Lethrinidae	*Lethrinus erythracanthus*	1862	Orange-spotted emperor
	Lethrinidae	*Lethrinus microdon*	1845	Smalltooth emperor
	Lethrinidae	*Lethrinus xanthochilus*	1852	Yellowlip emperor

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	Lutjanidae	*Lutjanus argentimaculatus*	1407	Mangrove red snapper
	Lutjanidae	*Lutjanus bohar*	1417	Two-spot red snapper
	Malacanthidae	*Malacanthus latovittatus*	5796	Blue blanquillo
	Megalopidae	*Megalops cyprinoides*	227	Indo-Pacific tarpon
	Lethrinidae	*Monotaxis grandoculis*	1869	Humpnose big-eye bream
	Ophichthidae	*Myrichthys colubrinus*	8053	Harlequin snake eel
	Ophichthidae	*Myrichthys maculosus*	2650	Tiger snake eel
	Acanthuridae	*Naso hexacanthus*	1263	Sleek unicornfish
	Balistidae	*Odonus niger*	1311	Redtoothed triggerfish
	Ophichthidae	*Ophichthus erabo*	15682	Fowler's snake eel
	Labridae	*Oxycheilinus digramma*	5599	Cheeklined wrasse
	Platycephalidae	*Papilloculiceps longiceps*	7896	Tentacled flathead
	Lutjanidae	*Paracaesio xanthura*	194	Yellowtail blue snapper
	Ophichthidae	*Phaenomonas cooperae*	15691	Short-maned sand-eel
	Lutjanidae	*Pinjalo pinjalo*	196	Pinjalo
	Ophichthidae	*Pisodonophis cancrivorus*	8054	Longfin snake-eel
	Ephippidae	*Platax orbicularis*	5737	Orbicular batfish
	Haemulidae	*Plectorhinchus albovittatus*	6362	Two-striped sweetlips
	Haemulidae	*Plectorhinchus nigrus*	23485	
	Haemulidae	*Plectorhinchus obscurus*	6368	Giant sweetlips
	Haemulidae	*Plectorhinchus playfairi*	7705	Whitebarred rubberlip
	Haemulidae	*Plectorhinchus schotaf*	7706	Minstrel sweetlip
	Haemulidae	*Plectorhinchus umbrinus*	60760	
	Sparidae	*Polysteganus coeruleopunctatus*	7935	Blueskin seabream
	Haemulidae	*Pomadasys commersonnii*	5126	Smallspotted grunter
	Haemulidae	*Pomadasys furcatus*	7707	Banded grunter
	Haemulidae	*Pomadasys kaakan*	6006	Javelin grunter
	Balistidae	*Pseudobalistes flavimarginatus*	6027	Yellowmargin triggerfish
	Balistidae	*Pseudobalistes fuscus*	4466	Yellow-spotted triggerfish
	Rachycentridae	*Rachycentron canadum*	3542	Cobia
	Echeneidae	*Remora remora*	1751	Common remora
	Sparidae	*Rhabdosargus sarba*	5368	Goldlined seabream
	Holocentridae	*Sargocentron spiniferum*	6507	Sabre squirrelfish
	Carangidae	*Trachinotus baillonii*	1978	Smallspotted dart
	Carangidae	*Trachinotus blochii*	1963	Snubnose pompano
	Carangidae	*Ulua mentalis*	1930	Longrakered trevally
	Muraenidae	*Uropterygius concolor*	7283	Unicolor snake moray
	Muraenidae	*Uropterygius polyspilus*	27347	Large-spotted snake moray
	Blenniidae	*Xiphasia setifer*	7563	Hairtail blenny
Medium reef carnivores	Pomacentridae	*Abudefduf bengalensis*	6517	Bengal sergeant
	Pomacentridae	*Abudefduf septemfasciatus*	5687	Banded sergeant
	Sparidae	*Acanthopagrus bifasciatus*	4543	Twobar seabream
	Centriscidae	*Aeoliscus punctulatus*	7986	Speckled shrimpfish
	Soleidae	*Aesopia cornuta*	7850	Unicorn sole
	Carangidae	*Alepes djedaba*	1889	Shrimp scad
	Ambassidae	*Ambassis commersonii*	13415	Commerson's glassy perchlet
	Labridae	*Anampses caeruleopunctatus*	4888	Bluespotted wrasse
	Labridae	*Anampses meleagrides*	4889	Spotted wrasse

Group	Family	Scientific name	FishBase Code	FishBase common name
	Labridae	*Anampses twistii*	4893	Yellowbreasted wrasse
	Apogonidae	*Apogon aureus*	4837	Ring-tailed cardinalfish
	Apogonidae	*Apogon kallopterus*	5758	Iridescent cardinalfish
	Apogonidae	*Apogon multitaeniatus*	8009	Smallscale cardinal
	Apogonidae	*Apogon taeniatus*	127	Twobelt cardinal
	Apogonidae	*Apogon truncatus*	58304	Flagfin cardinalfish
	Sparidae	*Argyrops filamentosus*	4541	Soldierbream
	Congridae	*Ariosoma balearicum*	1744	Bandtooth conger
	Congridae	*Ariosoma scheelei*	7672	Tropical conger
	Tetraodontidae	*Arothron diadematus*	25413	Masked puffer
	Tetraodontidae	*Arothron immaculatus*	7188	Immaculate puffer
	Tetraodontidae	*Arothron nigropunctatus*	6400	Blackspotted puffer
	Bothidae	*Asterorhombus intermedius*	8123	Intermediate flounder
	Atherinidae	*Atherinomorus lacunosus*	1303	Hardyhead silverside
	Serranidae	*Aulacocephalus temminckii*	7701	Goldribbon soapfish
	Balistidae	*Balistapus undulatus*	6025	Orange-lined triggerfish
	Labridae	*Bodianus anthioides*	5497	Lyretail hogfish
	Labridae	*Bodianus axillaris*	5498	Axilspot hogfish
	Labridae	*Bodianus diana*	5500	Diana's hogfish
	Labridae	*Bodianus opercularis*	25754	Blackspot hogfish
	Bothidae	*Bothus pantherinus*	1321	Leopard flounder
	Caesionidae	*Caesio caerulaurea*	918	Blue and gold fusilier
	Caesionidae	*Caesio lunaris*	920	Lunar fusilier
	Caesionidae	*Caesio striata*	921	Striated fusilier
	Caesionidae	*Caesio suevica*	922	Suez fusilier
	Caesionidae	*Caesio varilineata*	924	Variable-lined fusilier
	Caesionidae	*Caesio xanthonota*	927	Yellowback fusilier
	Plesiopidae	*Calloplesiops altivelis*	12655	Comet
	Monacanthidae	*Cantherhines dumerilii*	5836	Whitespotted filefish
	Monacanthidae	*Cantherhines pardalis*	6635	Honeycomb filefish
	Tetraodontidae	*Canthigaster margaritata*	12778	
	Carangidae	*Carangoides armatus*	1916	Longfin trevally
	Carapidae	*Carapus homei*	4832	Silver pearlfish
	Centriscidae	*Centriscus scutatus*	6510	Grooved razor-fish
	Chaetodontidae	*Chaetodon auriga*	5557	Threadfin butterflyfish
	Chaetodontidae	*Chaetodon austriacus*	6514	Blacktail butterflyfish
	Chaetodontidae	*Chaetodon collare*	7803	Redtail butterflyfish
	Chaetodontidae	*Chaetodon falcula*	8014	Blackwedged butterflyfish
	Chaetodontidae	*Chaetodon fasciatus*	12274	Diagonal butterflyfish
	Chaetodontidae	*Chaetodon kleinii*	5446	Sunburst butterflyfish
	Chaetodontidae	*Chaetodon lineolatus*	5564	Lined butterflyfish
	Chaetodontidae	*Chaetodon melannotus*	5566	Blackback butterflyfish
	Chaetodontidae	*Chaetodon semilarvatus*	12300	Bluecheek butterflyfish
	Chaetodontidae	*Chaetodon trifasciatus*	5579	Melon butterflyfish
	Chaetodontidae	*Chaetodon vagabundus*	5582	Vagabond butterflyfish
	Apogonidae	*Cheilodipterus arabicus*	6669	Tiger cardinal
	Apogonidae	*Cheilodipterus lachneri*	12630	
	Labridae	*Choerodon robustus*	6926	Robust tuskfish
	Labridae	*Cirrhilabrus blatteus*	25759	Purple-boned wrasse
	Cirrhitidae	*Cirrhitus pinnulatus*	5831	Stocky hawkfish
	Labridae	*Coris caudimacula*	8026	Spottail coris
	Labridae	*Coris cuvieri*	52844	African coris

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	Labridae	*Coris gaimard*	5625	Yellowtail coris
	Labridae	*Coris variegata*	5485	Dapple coris
	Syngnathidae	*Corythoichthys schultzi*	5965	Schultz's pipefish
	Diodontidae	*Cyclichthys orbicularis*	5196	Birdbeak burrfish
	Dactylopteridae	*Dactyloptena orientalis*	4485	Oriental flying gurnard
	Carangidae	*Decapterus macrosoma*	1938	Shortfin scad
	Scorpaenidae	*Dendrochirus brachypterus*	4912	Shortfin turkeyfish
	Scorpaenidae	*Dendrochirus zebra*	5828	Zebra turkeyfish
	Syngnathidae	*Doryrhamphus dactyliophorus*	5972	Ringed pipefish
	Syngnathidae	*Doryrhamphus multiannulatus*	14286	Many-banded pipefish
	Drepaneidae	*Drepane punctata*	454	Spotted sicklefish
	Clupeidae	*Dussumieria elopsoides*	1454	Slender rainbow sardine
	Carapidae	*Encheliophis gracilis*	9204	Graceful pearlfish
	Bothidae	*Engyprosopon grandisquama*	1324	Largescale flounder
	Serranidae	*Epinephelus merra*	4923	Honeycomb grouper
	Serranidae	*Epinephelus stoliczkae*	7364	Epaulet grouper
	Chaetodontidae	*Forcipiger flavissimus*	5584	Longnose butterflyfish
	Chaetodontidae	*Forcipiger longirostris*	5585	Longnose butterflyfish
	Pomacanthidae	*Genicanthus caudovittatus*	11132	Zebra angelfish
	Gerreidae	*Gerres argyreus*	5799	Common mojarra
	Gerreidae	*Gerres filamentosus*	4463	Whipfin silverbiddy
	Gerreidae	*Gerres longirostris*	7699	Longtail silverbiddy
	Gerreidae	*Gerres oblongus*	5801	Slender silverbiddy
	Gerreidae	*Gerres oyena*	5996	Common silver-biddy
	Labridae	*Gomphosus caeruleus*	7744	Green birdmouth wrasse
	Serranidae	*Grammistes sexlineatus*	4925	Sixline soapfish
	Caesionidae	*Gymnocaesio gymnoptera*	929	Slender fusilier
	Lethrinidae	*Gymnocranius griseus*	1833	Grey large-eye bream
	Muraenidae	*Gymnothorax buroensis*	6493	Vagrant moray
	Muraenidae	*Gymnothorax pindae*	7447	Pinda moray
	Syngnathidae	*Halicampus dunckeri*	5974	Duncker's pipefish
	Syngnathidae	*Halicampus grayi*	7727	Gray's pipefish
	Syngnathidae	*Halicampus macrorhynchus*	10225	Ornate pipefish
	Labridae	*Halichoeres bimaculatus*	50017	
	Labridae	*Halichoeres hortulanus*	12663	Checkerboard wrasse
	Labridae	*Halichoeres margaritaceus*	5630	Pink-belly wrasse
	Labridae	*Halichoeres marginatus*	5631	Dusky wrasse
	Labridae	*Halichoeres scapularis*	5633	Zigzag wrasse
	Labridae	*Halichoeres zeylonicus*	13050	Goldstripe wrasse
	Pseudochromidae	*Haliophis guttatus*	4428	African eel blenny
	Chaetodontidae	*Heniochus intermedius*	12309	Red Sea bannerfish
	Chaetodontidae	*Heniochus monoceros*	5590	Masked bannerfish
	Congridae	*Heteroconger hassi*	12619	Spotted garden-eel
	Syngnathidae	*Hippocampus histrix*	5954	Thorny seahorse
	Syngnathidae	*Hippocampus kuda*	5955	Spotted seahorse
	Pentacerotidae	*Histiopterus typus*	7892	Sailfin armourhead
	Hemiramphidae	*Hyporhamphus affinis*	7710	Tropical halfbeak
	Labridae	*Iniistius pavo*	5613	Peacock wrasse

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	Synanceiidae	*Inimicus filamentosus*	6403	Two-stick stingfish
	Ostraciidae	*Lactoria cornuta*	6399	Longhorn cowfish
	Ophichthidae	*Lamnostoma orientalis*	11728	Oriental worm-eel
	Leiognathidae	*Leiognathus equulus*	4451	Common ponyfish
	Lethrinidae	*Lethrinus borbonicus*	1844	Snubnose emperor
	Lethrinidae	*Lethrinus harak*	1851	Thumbprint emperor
	Lethrinidae	*Lethrinus obsoletus*	1847	Orange-striped emperor
	Lethrinidae	*Lethrinus variegatus*	1850	Slender emperor
	Lutjanidae	*Lutjanus bengalensis*	1409	Bengal snapper
	Lutjanidae	*Lutjanus coeruleolineatus*	1425	Blueline snapper
	Lutjanidae	*Lutjanus fulviflamma*	261	Dory snapper
	Lutjanidae	*Lutjanus gibbus*	265	Humpback red snapper
	Lutjanidae	*Lutjanus kasmira*	156	Common bluestripe snapper
	Malacanthidae	*Malacanthus brevirostris*	5795	Quakerfish
	Menidae	*Mene maculata*	390	Moonfish
	Monocentridae	*Monocentris japonica*	8183	Pineconefish
	Monodactylidae	*Monodactylus falciformis*	7858	Full moony
	Mullidae	*Mulloidichthys flavolineatus*	5983	Yellowstripe goatfish
	Mullidae	*Mulloidichthys vanicolensis*	5984	Yellowfin goatfish
	Ophichthidae	*Muraenichthys schultzei*	7290	Maimed snake eel
	Holocentridae	*Myripristis berndti*	4910	Blotcheye soldierfish
	Holocentridae	*Myripristis hexagona*	7305	Doubletooth soldierfish
	Holocentridae	*Myripristis murdjan*	5408	Pinecone soldierfish
	Holocentridae	*Myripristis xanthacra*	7822	Yellowtip soldierfish
	Carangidae	*Naucrates ductor*	998	Pilotfish
	Holocentridae	*Neoniphon sammara*	4911	Sammara squirrelfish
	Labridae	*Novaculichthys macrolepidotus*	5609	Seagrass wrasse
	Labridae	*Novaculichthys taeniourus*	5610	Rockmover wrasse
	Opistognathidae	*Opistognathus muscatensis*	8000	Robust jawfish
	Ostraciidae	*Ostracion cubicus*	6555	Yellow boxfish
	Ostraciidae	*Ostracion cyanurus*	12743	Bluetail trunkfish
	Labridae	*Oxycheilinus arenatus*	5595	Speckled maori wrasse
	Labridae	*Oxycheilinus bimaculatus*	5596	Two-spot wrasse
	Labridae	*Oxycheilinus mentalis*	12779	Mental wrasse
	Gobiidae	*Oxyurichthys papuensis*	8030	Frogface goby
	Pinguipedidae	*Parapercis hexophtalma*	7866	Speckled sandperch
	Carangidae	*Parastromateus niger*	1947	Black pomfret
	Soleidae	*Pardachirus marmoratus*	8917	Finless sole
	Mullidae	*Parupeneus forsskali*	10994	Red Sea goatfish
	Mullidae	*Parupeneus indicus*	5992	Indian goatfish
	Mullidae	*Parupeneus macronema*	7878	Longbarbel goatfish
	Mullidae	*Parupeneus rubescens*	6373	Rosy goatfish
	Terapontidae	*Pelates quadrilineatus*	7945	Fourlined terapon
	Pempheridae	*Pempheris oualensis*	5802	Silver sweeper
	Pempheridae	*Pempheris schwenkii*	12908	Black-stripe sweeper
	Pempheridae	*Pempheris vanicolensis*	10350	Vanikoro sweeper
	Gobiidae	*Periophthalmus argentilineatus*	7480	Barred mudskipper
	Platycephalidae	*Platycephalus indicus*	950	Bartail flathead
	Plesiopidae	*Plesiops nigricans*	24438	Whitespotted longfin

Group	Family	Scientific name	FishBase Code	FishBase common name
	Plotosidae	*Plotosus lineatus*	4706	Striped eel catfish
	Priacanthidae	*Priacanthus hamrur*	5791	Moontail bullseye
	Serranidae	*Pseudanthias squamipinnis*	6568	Sea goldie
	Labridae	*Pteragogus flagellifer*	8022	Cocktail wrasse
	Caesionidae	*Pterocaesio chrysozona*	932	Goldband fusilier
	Caesionidae	*Pterocaesio pisang*	936	Banana fusilier
	Scorpaenidae	*Pterois miles*	7797	Devil firefish
	Scorpaenidae	*Pterois radiata*	4913	Radial firefish
	Scorpaenidae	*Pterois russelii*	6404	Plaintail turkeyfish
	Sparidae	*Rhabdosargus haffara*	8166	Haffara seabream
	Balistidae	*Rhinecanthus aculeatus*	5839	Blackbar triggerfish
	Balistidae	*Rhinecanthus assasi*	25420	Picasso triggerfish
	Balistidae	*Rhinecanthus rectangulus*	5840	Wedge-tail triggerfish
	Balistidae	*Rhinecanthus verrucosus*	6028	Blackbelly triggerfish
	Holocentridae	*Sargocentron caudimaculatum*	4907	Silverspot squirrelfish
	Holocentridae	*Sargocentron diadema*	4699	Crown squirrelfish
	Holocentridae	*Sargocentron ittodai*	6573	Samurai squirrelfish
	Holocentridae	*Sargocentron punctatissimum*	4906	Speckled squirrelfish
	Holocentridae	*Sargocentron rubrum*	6625	Redcoat
	Ophichthidae	*Scolecenchelys gymnota*	7288	Slender worm eel
	Ophichthidae	*Scolecenchelys laticaudata*	15672	Redfin worm-eel
	Nemipteridae	*Scolopsis bimaculatus*	5886	Thumbprint monocle bream
	Nemipteridae	*Scolopsis ghanam*	5888	Arabian monocle bream
	Nemipteridae	*Scolopsis taeniatus*	5889	Black-streaked monocle bream
	Nemipteridae	*Scolopsis vosmeri*	5883	Whitecheek monocle bream
	Scorpaenidae	*Scorpaenopsis oxycephala*	5822	Tassled scorpionfish
	Scorpaenidae	*Scorpaenopsis venosa*	7919	Raggy scorpionfish
	Sillaginidae	*Sillago sihama*	4544	Silver sillago
	Soleidae	*Soleichthys heterorhinos*	22544	
	Solenostomidae	*Solenostomus cyanopterus*	7987	Ghost pipefish
	Labridae	*Stethojulis strigiventer*	5641	Three-ribbon wrasse
	Labridae	*Stethojulis trilineata*	6622	Three-lined rainbowfish
	Engraulidae	*Stolephorus indicus*	569	Indian anchovy
	Balistidae	*Sufflamen albicaudatum*	25419	Bluethroat triggerfish
	Balistidae	*Sufflamen fraenatum*	1312	Masked triggerfish
	Syngnathidae	*Syngnathoides biaculeatus*	5980	Alligator pipefish
	Synodontidae	*Synodus indicus*	7942	Indian lizardfish
	Terapontidae	*Terapon jarbua*	4458	Jarbua terapon
	Terapontidae	*Terapon theraps*	4829	Largescaled therapon
	Ostraciidae	*Tetrosomus gibbosus*	8129	Humpback turretfish
	Labridae	*Thalassoma hebraicum*	8019	Goldbar wrasse
	Labridae	*Thalassoma lunare*	5645	Moon wrasse
	Labridae	*Thalassoma purpureum*	5647	Surge wrasse
	Labridae	*Thalassoma rueppellii*	25787	Klunzinger's wrasse
	Labridae	*Thalassoma trilobatum*	5649	Christmas wrasse
	Monacanthidae	*Thamnaconus modestoides*	7855	Modest filefish
	Platycephalidae	*Thysanophrys chiltonae*	12902	Longsnout flathead
	Syngnathidae	*Trachyrhamphus*	5981	Double-ended pipefish

Group	Family	Scientific name	FishBase Code	FishBase common name
		bicoarctatus		
	Mullidae	*Upeneus moluccensis*	4444	Goldband goatfish
	Mullidae	*Upeneus tragula*	5443	Freckled goatfish
	Mullidae	*Upeneus vittatus*	4821	Yellowstriped goatfish
	Uranoscopidae	*Uranoscopus sulphureus*	13512	Whitemargin stargazer
	Carangidae	*Uraspis helvola*	1983	Whitemouth jack
	Carangidae	*Uraspis uraspis*	1984	Whitetongue jack
	Gobiidae	*Valenciennea helsdingenii*	7224	Twostripe goby
	Gobiidae	*Valenciennea puellaris*	7246	Maiden goby
	Blenniidae	*Xiphasia matsubarai*	6078	Japanese snake blenny
	Labridae	*Xyrichtys melanopus*	23517	Yellowpatch razorfish
	Labridae	*Xyrichtys pentadactylus*	7747	Fivefinger wrasse
	Gobiidae	*Yongeichthys nebulosus*	7228	Shadow goby
Small reef carnivores	Syngnathidae	*Acentronura tentaculata*	16862	
	Gobiidae	*Amblyeleotris diagonalis*	13152	
	Gobiidae	*Amblyeleotris periophthalma*	7231	Periophthalma prawn-goby
	Gobiidae	*Amblyeleotris steinitzi*	7195	Steinitz' prawn-goby
	Gobiidae	*Amblyeleotris sungami*	12699	Magnus' prawn-goby
	Gobiidae	*Amblyeleotris wheeleri*	7196	Gorgeous prawn-goby
	Pomacentridae	*Amblyglyphidodon leucogaster*	5691	Yellowbelly damselfish
	Gobiidae	*Amblygobius esakiae*	27553	Snoutspot goby
	Labridae	*Anampses lineatus*	7800	Lined wrasse
	Antennariidae	*Antennarius rosaceus*	7296	Spiny-tufted frogfish
	Antennariidae	*Antennatus tuberosus*	11150	Tuberculated frogfish
	Apogonidae	*Apogon angustatus*	5766	Broadstriped cardinalfish
	Apogonidae	*Apogon annularis*	56240	Ringtail cardinalfish
	Apogonidae	*Apogon bandanensis*	5763	Bigeye cardinalfish
	Apogonidae	*Apogon coccineus*	5752	Ruby cardinalfish
	Apogonidae	*Apogon cookii*	9240	Cook's cardinalfish
	Apogonidae	*Apogon cyanosoma*	4600	Yellowstriped cardinalfish
	Apogonidae	*Apogon exostigma*	5756	Narrowstripe cardinalfish
	Apogonidae	*Apogon fasciatus*	6605	Broad-banded cardinalfish
	Apogonidae	*Apogon fraenatus*	5757	Bridled cardinalfish
	Apogonidae	*Apogon guamensis*	5765	Guam cardinalfish
	Apogonidae	*Apogon heptastygma*	50885	
	Apogonidae	*Apogon isus*	50886	
	Apogonidae	*Apogon kiensis*	8230	Rifle cardinal
	Apogonidae	*Apogon lateralis*	5761	Humpback cardinal
	Apogonidae	*Apogon latus*	60370	
	Apogonidae	*Apogon leptacanthus*	5773	Threadfin cardinalfish
	Apogonidae	*Apogon nigripinnis*	8012	Bullseye
	Apogonidae	*Apogon nigrofasciatus*	4836	Blackstripe cardinalfish
	Apogonidae	*Apogon pselion*	4839	
	Apogonidae	*Apogon pseudotaeniatus*	26632	Doublebar cardinalfish
	Apogonidae	*Apogon savayensis*	5764	Samoan cardinalfish
	Apogonidae	*Apogon semiornatus*	8008	Oblique-banded cardinalfish
	Apogonidae	*Apogon taeniophorus*	5767	Reef-flat cardinalfish
	Apogonidae	*Apogon timorensis*	12658	Timor cardinalfish
	Apogonidae	*Apogon zebrinus*	58157	
	Apogonidae	*Apogonichthys perdix*	5741	Perdix cardinalfish
	Apogonidae	*Archamia bilineata*	58158	

Group	Family	Scientific name	FishBase Code	FishBase common name
	Apogonidae	*Archamia fucata*	5776	Orangelined cardinalfish
	Apogonidae	*Archamia irida*	58159	
	Apogonidae	*Archamia lineolata*	7854	Shimmering cardinal
	Blenniidae	*Aspidontus taeniatus taeniatus*	6066	False cleanerfish
	Gobiidae	*Asterropteryx ensifera*	7247	Miller's damsel
	Gobiidae	*Bathygobius cyclopterus*	11801	Spotted frillgoby
	Gobiidae	*Bathygobius fuscus*	7201	Dusky frillgoby
	Bythitidae	*Brosmophyciops pautzkei*	7299	Slimy cuskeel
	Gobiidae	*Bryaninops erythrops*	7204	Erythrops goby
	Gobiidae	*Bryaninops loki*	52430	Loki whip-goby
	Gobiidae	*Bryaninops natans*	7205	Redeye goby
	Gobiidae	*Bryaninops ridens*	7250	Ridens goby
	Gobiidae	*Bryaninops yongei*	7251	Whip coral goby
	Callionymidae	*Callionymus delicatulus*	17467	Delicate dragonet
	Callionymidae	*Callionymus flavus*	56497	
	Gobiidae	*Callogobius bifasciatus*	46389	Doublebar goby
	Gobiidae	*Callogobius maculipinnis*	7206	Ostrich goby
	Tetraodontidae	*Canthigaster coronata*	7845	Crowned puffer
	Tetraodontidae	*Canthigaster pygmaea*	25414	Pygmy toby
	Chaetodontidae	*Chaetodon citrinellus*	5561	Speckled butterflyfish
	Chaetodontidae	*Chaetodon guttatissimus*	7791	Peppered butterflyfish
	Chaetodontidae	*Chaetodon larvatus*	12287	Hooded butterflyfish
	Chaetodontidae	*Chaetodon melapterus*	12533	Arabian butterflyfish
	Chaetodontidae	*Chaetodon mesoleucos*	25428	White-face butterflyfish
	Chaetodontidae	*Chaetodon paucifasciatus*	12296	Eritrean butterflyfish
	Chaetodontidae	*Chaetodon trifascialis*	5578	Chevron butterflyfish
	Apogonidae	*Cheilodipterus quinquelineatus*	5482	Five-lined cardinalfish
	Pseudochromidae	*Chlidichthys johnvoelckeri*	23591	Cerise dottyback
	Syngnathidae	*Choeroichthys brachysoma*	5958	Short-bodied pipefish
	Pomacentridae	*Chromis flavaxilla*	26638	Arabian chromis
	Pomacentridae	*Chromis nigrura*	12424	Blacktail chromis
	Pomacentridae	*Chromis ternatensis*	5677	Ternate chromis
	Pomacentridae	*Chromis weberi*	5680	Weber's chromis
	Labridae	*Cirrhilabrus rubriventralis*	12781	Social wrasse
	Cirrhitidae	*Cirrhitichthys calliurus*	46372	Spottedtail hawkfish
	Cirrhitidae	*Cirrhitichthys oxycephalus*	5830	Coral hawkfish
	Syngnathidae	*Corythoichthys flavofasciatus*	5959	Network pipefish
	Syngnathidae	*Corythoichthys nigripectus*	5962	Black-breasted pipefish
	Syngnathidae	*Cosmocampus banneri*	5966	Roughridge pipefish
	Syngnathidae	*Cosmocampus maxweberi*	5968	Maxweber's pipefish
	Gobiidae	*Cryptocentrus caeruleopunctatus*	12748	Harlequin prawn-goby
	Gobiidae	*Cryptocentrus cryptocentrus*	25797	Ninebar prawn-goby
	Gobiidae	*Cryptocentrus fasciatus*	12679	Y-bar shrimp goby
	Gobiidae	*Cryptocentrus lutheri*	25800	Luther's prawn-goby

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	Gobiidae	*Ctenogobiops crocineus*	13153	Silverspot shrimpgoby
	Gobiidae	*Ctenogobiops feroculus*	7238	Sandy prawn-goby
	Gobiidae	*Ctenogobiops maculosus*	27561	
	Gobiidae	*Discordipinna griessingeri*	7212	Spikefin goby
	Syngnathidae	*Doryrhamphus excisus abbreviatus*	7718	
	Engraulidae	*Encrasicholina punctifer*	558	Buccaneer anchovy
	Tripterygiidae	*Enneapterygius abeli*	16974	Yellow triplefin
	Pegasidae	*Eurypegasus draconis*	4606	Short dragonfish
	Gobiidae	*Eviota distigma*	7261	Twospot pygmy goby
	Gobiidae	*Eviota guttata*	25452	Spotted pygmy goby
	Gobiidae	*Eviota pardalota*	46398	Leopard dwarfgoby
	Gobiidae	*Eviota prasina*	7270	Green bubble goby
	Gobiidae	*Eviota sebreei*	7275	Sebree's pygmy goby
	Gobiidae	*Eviota zebrina*	25462	
	Gobiidae	*Flabelligobius latruncularia*	25463	Fan shrimp-goby
	Apogonidae	*Fowleria aurita*	8010	Crosseyed cardinalfish
	Apogonidae	*Fowleria marmorata*	5744	Marbled cardinalfish
	Apogonidae	*Fowleria punctulata*	5743	Spotcheek cardinalfish
	Apogonidae	*Fowleria vaiulae*	8592	Mottled cardinalfish
	Apogonidae	*Fowleria variegata*	5745	Variegated cardinalfish
	Gobiidae	*Fusigobius longispinus*	12834	Orange-spotted sand-goby
	Gobiidae	*Gladiogobius ensifer*	11174	Gladiator goby
	Gobiidae	*Gnatholepis anjerensis*	23595	
	Gobiidae	*Gobiodon citrinus*	7789	Poison goby
	Gobiidae	*Gobiodon reticulatus*	46399	Reticulate goby
	Microdesmidae	*Gunnellichthys monostigma*	12678	Onespot wormfish
	Apogonidae	*Gymnapogon melanogaster*	60031	
	Syngnathidae	*Halicampus mataafae*	5975	Samoan pipefish
	Labridae	*Halichoeres iridis*	12790	
	Labridae	*Halichoeres nebulosus*	6663	Nebulous wrasse
	Clupeidae	*Herklotsichthys quadrimaculatus*	1494	Bluestripe herring
	Atherinidae	*Hypoatherina barnesi*	1305	Barnes' silverside
	Atherinidae	*Hypoatherina temminckii*	1307	Samoan silverside
	Gobiidae	*Istigobius decoratus*	4328	Decorated goby
	Gobiidae	*Istigobius ornatus*	4322	Ornate goby
	Labridae	*Labroides dimidiatus*	5459	Bluestreak cleaner wrasse
	Labridae	*Larabicus quadrilineatus*	25788	Fourline wrasse
	Gobiesocidae	*Lepadichthys lineatus*	23229	Doubleline clingfish
	Serranidae	*Liopropoma mitratum*	8432	Pinstriped basslet
	Serranidae	*Liopropoma susumi*	7318	Meteor perch
	Gobiidae	*Luposicya lupus*	23719	
	Labridae	*Macropharyngodon bipartitus bipartitus*	7801	Vermiculate wrasse
	Labridae	*Macropharyngodon bipartitus marisrubri*	13137	
	Blenniidae	*Meiacanthus nigrolineatus*	12641	Blackline fangblenny
	Syngnathidae	*Micrognathus andersonii*	5977	Shortnose pipefish

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	Labridae	*Minilabrus striatus*	25781	Minute wrasse
	Apogonidae	*Neamia octospina*	8593	Eightspine cardinalfish
	Pomacentridae	*Neopomacentrus cyanomos*	8209	Regal demoiselle
	Pomacentridae	*Neopomacentrus miryae*	12461	Miry's demoiselle
	Pomacentridae	*Neopomacentrus xanthurus*	12464	Red Sea demoiselle
	Tripterygiidae	*Norfolkia brachylepis*	14209	Tropical scaly-headed triplefin
	Gobiidae	*Oplopomus oplopomus*	7218	Spinecheek goby
	Cirrhitidae	*Oxycirrhites typus*	5833	Longnose hawkfish
	Monacanthidae	*Oxymonacanthus halli*	25418	Red Sea longnose filefish
	Gobiidae	*Palutrus meteori*	25042	Meteor goby
	Labridae	*Paracheilinus octotaenia*	4840	Red Sea eightline flasher
	Gobiidae	*Paragobiodon echinocephalus*	7219	Redhead goby
	Gobiidae	*Paragobiodon xanthosomus*	7220	Emerald coral goby
	Pempheridae	*Parapriacanthus ransonneti*	5803	Pigmy sweeper
	Scorpaenidae	*Parascorpaena aurita*	27438	
	Scorpaenidae	*Parascorpaena mossambica*	5810	Mozambique scorpionfish
	Pseudochromidae	*Pectinochromis lubbocki*	12742	
	Anomalopidae	*Photoblepharon steinitzi*	17085	Flashlight fish
	Syngnathidae	*Phoxocampus belcheri*	7742	Rock pipefish
	Serranidae	*Plectranthias nanus*	15118	Bownband perchlet
	Serranidae	*Plectranthias winniensis*	12799	Redblotch basslet
	Plesiopidae	*Plesiops coeruleolineatus*	8005	Crimsontip longfin
	Gobiidae	*Pleurosicya mossambica*	23079	Toothy goby
	Pomacentridae	*Pomacentrus pavo*	5726	Sapphire damsel
	Gobiidae	*Priolepis cincta*	7221	Girdled goby
	Gobiidae	*Priolepis randalli*	46409	Randall's goby
	Pomacentridae	*Pristotis obtusirostris*	8127	Gulf damselfish
	Apogonidae	*Pseudamia gelatinosa*	4362	Gelatinous cardinalfish
	Serranidae	*Pseudanthias cichlops*	6945	
	Serranidae	*Pseudanthias heemstrai*	24434	Orangehead anthias
	Serranidae	*Pseudanthias lunulatus*	23329	Lunate goldie
	Serranidae	*Pseudanthias taeniatus*	12776	
	Labridae	*Pseudocheilinus evanidus*	5616	Striated wrasse
	Labridae	*Pseudocheilinus hexataenia*	5617	Pyjama
	Pseudochromidae	*Pseudochromis dixurus*	24442	Forktail dottyback
	Pseudochromidae	*Pseudochromis flavivertex*	12738	Sunrise dottyback
	Pseudochromidae	*Pseudochromis fridmani*	12741	Orchid dottyback
	Pseudochromidae	*Pseudochromis olivaceus*	24440	Olive dottyback
	Pseudochromidae	*Pseudochromis pesi*	12653	Pale dottyback
	Pseudochromidae	*Pseudochromis sankeyi*	24443	Striped dottyback
	Pseudochromidae	*Pseudochromis springeri*	24441	Blue-striped dottyback
	Pseudochromidae	*Pseudochromis xanthochir*	23434	
	Serranidae	*Pseudogramma megamycterum*	49434	
	Labridae	*Pteragogus cryptus*	5620	Cryptic wrasse
	Microdesmidae	*Ptereleotris evides*	4375	Blackfin dartfish

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	Microdesmidae	*Ptereleotris heteroptera*	4378	Blacktail goby
	Microdesmidae	*Ptereleotris microlepis*	4381	Blue gudgeon
	Microdesmidae	*Ptereleotris zebra*	4384	Chinese zebra goby
	Apogonidae	*Rhabdamia cypselura*	5746	Swallowtail cardinalfish
	Apogonidae	*Rhabdamia nigrimentum*	46488	
	Holocentridae	*Sargocentron inaequalis*	23249	Lattice squirrelfish
	Scorpaenidae	*Scorpaenodes corallinus*	27363	
	Scorpaenidae	*Scorpaenodes guamensis*	5819	Guam scorpionfish
	Scorpaenidae	*Scorpaenodes hirsutus*	5815	Hairy scorpionfish
	Scorpaenidae	*Scorpaenodes parvipinnis*	4915	Lowfin scorpionfish
	Scorpaenidae	*Scorpaenodes scaber*	7314	Pygmy scorpionfish
	Scorpaenidae	*Scorpaenodes varipinnis*	5818	Blotchfin scorpionfish
	Scorpaenidae	*Scorpaenopsis vittapinna*	59507	
	Scorpaenidae	*Sebastapistes bynoensis*	59579	
	Scorpaenidae	*Sebastapistes cyanostigma*	5811	Yellowspotted scorpionfish
	Scorpaenidae	*Sebastapistes strongia*	5814	Barchin scorpionfish
	Syngnathidae	*Siokunichthys bentuviai*	7194	
	Solenostomidae	*Solenostomus paradoxus*	7312	Harlequin ghost pipefish
	Clupeidae	*Spratelloides delicatulus*	1457	Delicate round herring
	Labridae	*Stethojulis albovittata*	8025	Bluelined wrasse
	Labridae	*Stethojulis interrupta*	6633	Cutribbon wrasse
	Pomacentridae	*Teixeirichthys jordani*	10742	Jordan's damsel
	Tetraodontidae	*Torquigener flavimaculosus*	26639	
	Gobiidae	*Trimma avidori*	28069	
	Gobiidae	*Trimma barralli*	28063	
	Gobiidae	*Trimma fishelsoni*	28070	
	Gobiidae	*Trimma flavicaudatus*	28071	
	Gobiidae	*Trimma mendelssohni*	28072	
	Gobiidae	*Trimma sheppardi*	28073	
	Gobiidae	*Trimma taylori*	12752	Yellow cave goby
	Gobiidae	*Trimma tevegae*	12754	Blue-striped cave goby
	Gobiidae	*Valenciennea sexguttata*	7227	Sixspot goby
	Gobiidae	*Valenciennea wardii*	12615	Ward's sleeper
	Gobiidae	*Vanderhorstia delagoae*	8033	Candystick goby
	Gobiidae	*Vanderhorstia mertensi*	23647	Mertens' prawn-goby
	Labridae	*Wetmorella nigropinnata*	4870	Sharpnose wrasse
	Xenisthmidae	*Xenisthmus polyzonatus*	13766	Bullseye wriggler
Reef omnivores	Pomacentridae	*Abudefduf sexfasciatus*	5688	Scissortail sergeant
	Pomacentridae	*Abudefduf sordidus*	5689	Blackspot sergeant
	Acanthuridae	*Acanthurus gahhm*	17471	Black surgeonfish
	Acanthuridae	*Acanthurus mata*	1255	Elongate surgeonfish
	Acanthuridae	*Acanthurus xanthopterus*	1261	Yellowfin surgeonfish
	Monacanthidae	*Aluterus scriptus*	4275	Scrawled filefish
	Monacanthidae	*Amanses scopas*	6672	Broom filefish
	Pomacentridae	*Amblyglyphidodon flavilatus*	11834	Yellowfin damsel
	Gobiidae	*Amblygobius albimaculatus*	6675	Butterfly goby
	Gobiidae	*Amblygobius hectori*	7242	Hector's goby
	Gobiidae	*Amblygobius nocturnus*	7243	Nocturn goby
	Pomacentridae	*Amphiprion bicinctus*	11837	Twoband anemonefish
	Pomacanthidae	*Apolemichthys xanthotis*	10940	Yellow-ear angelfish

Group	Family	Scientific name	FishBase Code	FishBase common name
	Blenniidae	*Aspidontus taeniatus tractus*	8040	
	Gobiidae	*Asterropteryx semipunctata*	7200	Starry goby
	Blenniidae	*Blenniella cyanostigma*	16946	Striped rockskipper
	Blenniidae	*Blenniella periophthalmus*	6051	Blue-dashed rockskipper
	Scaridae	*Bolbometopon muricatum*	5537	Green humphead parrotfish
	Pomacanthidae	*Centropyge bicolor*	5454	Bicolor angelfish
	Pomacanthidae	*Centropyge multispinis*	6549	Dusky angelfish
	Chaetodontidae	*Chaetodon leucopleura*	8083	Somali butterflyfish
	Chanidae	*Chanos chanos*	80	Milkfish
	Scaridae	*Chlorurus gibbus*	4979	Heavybeak parrotfish
	Pomacentridae	*Chromis dimidiata*	11861	Chocolatedip chromis
	Pomacentridae	*Chromis pelloura*	12428	Duskytail chromis
	Pomacentridae	*Chromis pembae*	12429	Pemba chromis
	Pomacentridae	*Chromis trialpha*	12432	Trispot chromis
	Pomacentridae	*Chromis viridis*	5679	Blue green damselfish
	Pomacentridae	*Chrysiptera annulata*	12438	Footballer demoiselle
	Pomacentridae	*Chrysiptera unimaculata*	5702	Onespot demoiselle
	Mugilidae	*Crenimugil crenilabis*	5653	Fringelip mullet
	Pomacentridae	*Dascyllus aruanus*	5110	Whitetail dascyllus
	Pomacentridae	*Dascyllus marginatus*	11985	Marginate dascyllus
	Pomacentridae	*Dascyllus trimaculatus*	5112	Threespot dascyllus
	Sparidae	*Diplodus noct*	8112	Red Sea seabream
	Blenniidae	*Ecsenius midas*	7561	Persian blenny
	Tripterygiidae	*Enneapterygius altipinnis*	13574	Highfin triplefin
	Tripterygiidae	*Enneapterygius tutuilae*	47045	High hat triplefin
	Blenniidae	*Exallias brevis*	6032	Leopard blenny
	Gobiidae	*Exyrias belissimus*	370	Mud reef-goby
	Gobiidae	*Fusigobius neophytus*	7215	Common fusegoby
	Gobiidae	*Gnatholepis cauerensis cauerensis*	9950	Eyebar goby
	Tripterygiidae	*Helcogramma steinitzi*	26343	Red triplefin
	Hemiramphidae	*Hemiramphus far*	5404	Blackbarred halfbeak
	Hemiramphidae	*Hyporhamphus balinensis*	16813	Balinese garfish
	Hemiramphidae	*Hyporhamphus gamberur*	53427	Red Sea halfbeak
	Scaridae	*Leptoscarus vaigiensis*	4360	Marbled parrotfish
	Mugilidae	*Liza vaigiensis*	5656	Squaretail mullet
	Balistidae	*Melichthys indicus*	7634	Indian triggerfish
	Blenniidae	*Mimoblennius cirrosus*	46416	Fringed blenny
	Acanthuridae	*Naso annulatus*	6019	Whitemargin unicornfish
	Acanthuridae	*Naso brevirostris*	6021	Spotted unicornfish
	Acanthuridae	*Naso elegans*	60074	Elegant unicornfish
	Pomacentridae	*Neoglyphidodon melas*	5707	Bowtie damselfish
	Mugilidae	*Oedalechilus labiosus*	5657	Hornlip mullet
	Blenniidae	*Omobranchus punctatus*	7566	Muzzled blenny
	Lutjanidae	*Paracaesio sordida*	192	Dirty ordure snapper
	Monacanthidae	*Paramonacanthus japonicus*	7977	Hairfinned leatherjacket
	Monacanthidae	*Pervagor randalli*	4372	
	Blenniidae	*Plagiotremus rhinorhynchos*	6071	Bluestriped fangblenny
	Blenniidae	*Plagiotremus tapeinosoma*	6072	Piano fangblenny

Group	Family	Scientific name	FishBase Code	FishBase common name
	Pomacentridae	*Plectroglyphidodon lacrymatus*	5712	Whitespotted devil
	Pomacanthidae	*Pomacanthus asfur*	11194	Arabian angelfish
	Pomacanthidae	*Pomacanthus imperator*	6504	Emperor angelfish
	Pomacanthidae	*Pomacanthus maculosus*	7903	Yellowbar angelfish
	Pomacanthidae	*Pomacanthus semicirculatus*	5663	Semicircle angelfish
	Pomacentridae	*Pomacentrus albicaudatus*	12478	Whitefin damsel
	Pomacentridae	*Pomacentrus aquilus*	12480	Dark damsel
	Pomacentridae	*Pomacentrus leptus*	12494	Slender damsel
	Pomacentridae	*Pomacentrus sulfureus*	12503	Sulphur damsel
	Pomacentridae	*Pomacentrus trichourus*	12504	Paletail damsel
	Pomacentridae	*Pomacentrus trilineatus*	12505	Threeline damsel
	Haemulidae	*Pomadasys olivaceus*	5518	Olive grunt
	Gobiidae	*Priolepis semidoliata*	12885	Half-barred goby
	Pomacentridae	*Pristotis cyanostigma*	12507	Bluedotted damsel
	Labridae	*Pseudodax moluccanus*	5594	Chiseltooth wrasse
	Pomacanthidae	*Pygoplites diacanthus*	6572	Royal angelfish
	Blenniidae	*Salarias fasciatus*	6058	Jewelled blenny
	Clupeidae	*Sardinella albella*	1502	White sardinella
	Scaridae	*Scarus caudofasciatus*	7908	Redbarred parrotfish
	Scaridae	*Scarus collana*	14379	Red Sea parrotfish
	Scaridae	*Scarus fuscopurpureus*	14381	Purple-brown parrotfish
	Siganidae	*Siganus javus*	4618	Streaked spinefoot
	Siganidae	*Siganus stellatus*	4622	Brownspotted spinefoot
	Pomacentridae	*Stegastes lividus*	4351	Blunt snout gregory
	Pomacentridae	*Stegastes nigricans*	4352	Dusky farmerfish
	Mugilidae	*Valamugil seheli*	5659	Bluespot mullet
Reef herbivores	Acanthuridae	*Acanthurus nigricans*	6011	Whitecheek surgeonfish
	Acanthuridae	*Acanthurus nigrofuscus*	4739	Brown surgeonfish
	Acanthuridae	*Acanthurus sohal*	4740	Sohal surgeonfish
	Acanthuridae	*Acanthurus tennentii*	1259	Doubleband surgeonfish
	Blenniidae	*Aspidontus dussumieri*	6065	Lance blenny
	Blenniidae	*Atrosalarias fuscus fuscus*	17462	
	Scaridae	*Calotomus viridescens*	4358	Viridescent parrotfish
	Scaridae	*Cetoscarus bicolor*	5538	Bicolour parrotfish
	Scaridae	*Chlorurus genazonatus*	14382	Sinai parrotfish
	Scaridae	*Chlorurus sordidus*	5556	Daisy parrotfish
	Pomacentridae	*Chrysiptera biocellata*	5693	Twinspot damselfish
	Blenniidae	*Cirripectes castaneus*	4387	Chestnut eyelash-blenny
	Blenniidae	*Cirripectes filamentosus*	4389	Filamentous blenny
	Acanthuridae	*Ctenochaetus striatus*	1262	Striated surgeonfish
	Blenniidae	*Ecsenius aroni*	25794	Aron's blenny
	Blenniidae	*Ecsenius frontalis*	12634	Smooth-fin blenny
	Blenniidae	*Ecsenius gravieri*	12635	Red Sea mimic blenny
	Blenniidae	*Ecsenius nalolo*	25451	Nalolo
	Blenniidae	*Enchelyurus kraussii*	6062	Krauss' blenny
	Scaridae	*Hipposcarus harid*	7906	Candelamoa parrotfish
	Blenniidae	*Istiblennius edentulus*	6049	Rippled rockskipper
	Blenniidae	*Istiblennius rivulatus*	23697	
	Kyphosidae	*Kyphosus bigibbus*	5804	Grey sea chub
	Kyphosidae	*Kyphosus vaigiensis*	5806	Brassy chub
	Acanthuridae	*Naso unicornis*	1265	Bluespine unicornfish

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	Blenniidae	*Petroscirtes mitratus*	6074	Floral blenny
	Blenniidae	*Plagiotremus townsendi*	12788	Townsend's fangblenny
	Pomacentridae	*Plectroglyphidodon leucozonus*	5713	Singlebar devil
	Scaridae	*Scarus ferrugineus*	14380	Rusty parrotfish
	Scaridae	*Scarus frenatus*	5546	Bridled parrotfish
	Scaridae	*Scarus niger*	5550	Dusky parrotfish
	Scaridae	*Scarus psittacus*	5553	Common parrotfish
	Scaridae	*Scarus russelii*	7912	Eclipse parrotfish
	Scaridae	*Scarus scaber*	7913	Fivesaddle parrotfish
	Siganidae	*Siganus argenteus*	4614	Streamlined spinefoot
	Siganidae	*Siganus luridus*	4613	Dusky spinefoot
	Siganidae	*Siganus rivulatus*	4545	Marbled spinefoot
	Acanthuridae	*Zebrasoma veliferum*	1266	Sailfin tang
	Acanthuridae	*Zebrasoma xanthurum*	12023	Yellowtail tang
Large pelagic carnivores	Coryphaenidae	*Coryphaena hippurus*	6	Common dolphinfish
	Elopidae	*Elops machnata*	5512	Tenpounder
	Istiophoridae	*Istiophorus platypterus*	77	Indo-Pacific sailfish
	Istiophoridae	*Makaira indica*	217	Black marlin
	Molidae	*Mola mola*	1732	Ocean sunfish
	Molidae	*Ranzania laevis*	1750	Slender sunfish
	Scombridae	*Sarda orientalis*	114	Striped bonito
	Carangidae	*Scomber sansun*	53238	
	Istiophoridae	*Tetrapturus audax*	223	Striped marlin
	Scombridae	*Thunnus albacares*	143	Yellowfin tuna
	Belonidae	*Tylosurus choram*	26633	Red Sea houndfish
	Xiphiidae	*Xiphias gladius*	226	Swordfish
Small pelagic carnivores	Carangidae	*Alepes vari*	1891	Herring scad
	Clupeidae	*Amblygaster leiogaster*	1500	Smooth-belly sardinella
	Scombridae	*Auxis rochei rochei*	93	Bullet tuna
	Scombridae	*Auxis thazard thazard*	94	Frigate tuna
	Bregmacerotidae	*Bregmaceros mcclellandii*	8421	Spotted codlet
	Bregmacerotidae	*Bregmaceros nectabanus*	8422	Smallscale codlet
	Carangidae	*Carangoides ciliarius*	53230	
	Exocoetidae	*Cheilopogon cyanopterus*	7695	Margined flyingfish
	Exocoetidae	*Cheilopogon pinnatibarbatus altipennis*	23233	Smallhead flyingfish
	Chirocentridae	*Chirocentrus nudus*	1452	Whitefin wolf-herring
	Coryphaenidae	*Coryphaena equiselis*	7	Pompano dolphinfish
	Exocoetidae	*Cypselurus oligolepis*	15365	Largescale flyingfish
	Carangidae	*Decapterus macarellus*	993	Mackerel scad
	Clupeidae	*Dussumieria acuta*	1453	Rainbow sardine
	Engraulidae	*Engraulis encrasicolus*	66	European anchovy
	Hemiramphidae	*Euleptorhamphus viridis*	3156	Ribbon halfbeak
	Exocoetidae	*Exocoetus volitans*	1032	Tropical two-wing flyingfish
	Hemiramphidae	*Hemiramphus marginatus*	9963	Yellowtip halfbeak
	Clupeidae	*Herklotsichthys lossei*	1492	Gulf herring
	Clupeidae	*Hilsa kelee*	1595	Kelee shad
	Exocoetidae	*Hirundichthys rondeletii*	1035	Black wing flyingfish
	Exocoetidae	*Hirundichthys socotranus*	60693	
	Malacanthidae	*Hoplolatilus geo*	54468	
	Hemiramphidae	*Hyporhamphus xanthopterus*	25044	Red-tipped halfbeak

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	Scombridae	*Katsuwonus pelamis*	107	Skipjack tuna
	Lactariidae	*Lactarius lactarius*	363	False trevally
	Exocoetidae	*Parexocoetus brachypterus*	1037	Sailfin flyingfish
	Exocoetidae	*Parexocoetus mento*	4904	African sailfin flyingfish
	Belonidae	*Platybelone argalus platura*	58272	
	Echeneidae	*Remora brachyptera*	3546	Spearfish remora
	Echeneidae	*Remorina albescens*	3548	White suckerfish
	Scombridae	*Scomber japonicus*	117	Chub mackerel
	Sphyraenidae	*Sphyraena chrysotaenia*	16905	Yellowstripe barracuda
	Clupeidae	*Spratelloides gracilis*	1458	Silver-stripe round herring
	Engraulidae	*Thryssa setirostris*	599	Longjaw thryssa
Pelagic omnivores	Bregmacerotidae	*Bregmaceros arabicus*	23168	
	Leiognathidae	*Leiognathus oblongus*	58321	Oblong ponyfish
	Mugilidae	*Liza carinata*	13673	Keeled mullet
	Monodactylidae	*Monodactylus argenteus*	5807	Silver moony
	Clupeidae	*Sardinella longiceps*	1511	Indian oil sardine
Demersal top predator	Muraenesocidae	*Congresox talabonoides*	11713	Indian pike conger
	Serranidae	*Epinephelus epistictus*	7341	Dotted grouper
	Serranidae	*Epinephelus radiatus*	7360	Oblique-banded grouper
	Leiognathidae	*Gazza minuta*	4462	Toothpony
	Gobiidae	*Glossogobius giuris*	4833	Tank goby
	Muraenidae	*Gymnothorax johnsoni*	7882	Whitespotted moray
	Lophiidae	*Lophiomus setigerus*	7517	Blackmouth angler
	Muraenesocidae	*Muraenesox cinereus*	298	Daggertooth pike conger
	Psettodidae	*Psettodes erumei*	513	Indian spiny turbot
	Paralichthyidae	*Pseudorhombus arsius*	1325	Largetooth flounder
	Synodontidae	*Synodus hoshinonis*	7941	Blackear lizardfish
	Synodontidae	*Synodus macrops*	8299	Triplecross lizardfish
	Uranoscopidae	*Uranoscopus bauchotae*	56492	
	Uranoscopidae	*Uranoscopus dahlakensis*	56493	
	Uranoscopidae	*Uranoscopus oligolepis*	8303	
	Sparidae	*Argyrops megalommatus*	61176	
Large demersal carnivores	Ariidae	*Arius thalassinus*	10220	Giant seacatfish
	Malacanthidae	*Branchiostegus sawakinensis*	7649	Freckled tilefish
	Labridae	*Cheilinus abudjubbe*	60813	
	Cynoglossidae	*Cynoglossus arel*	7523	Largescale tonguesole
	Cynoglossidae	*Cynoglossus bilineatus*	5455	Fourlined tonguesole
	Serranidae	*Epinephelus latifasciatus*	7350	Striped grouper
	Congridae	*Gorgasia cotroneii*	58702	
	Congridae	*Gorgasia sillneri*	55167	
	Muraenidae	*Gymnothorax angusticauda*	27319	
	Muraenidae	*Gymnothorax tile*	17266	
	Gymnuridae	*Gymnura poecilura*	8260	Longtail butterfly ray
	Tetraodontidae	*Lagocephalus lunaris*	8263	Green rough-backed puffer
	Tetraodontidae	*Lagocephalus spadiceus*	8180	Half-smooth golden pufferfish
	Platycephalidae	*Platycephalus micracanthus*	52981	
	Haemulidae	*Plectorhinchus faetela*	60766	

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	Haemulidae	*Pomadasys argenteus*	399	Silver grunt
	Haemulidae	*Pomadasys hasta*	55178	
	Haemulidae	*Pomadasys multimaculatum*	5517	Cock grunter
	Lutjanidae	*Pristipomoides multidens*	208	Goldbanded jobfish
	Platycephalidae	*Rogadius pristiger*	15225	Thorny flathead
	Nettastomatidae	*Saurenchelys lateromaculatus*	58723	
	Congridae	*Uroconger lepturus*	7590	Slender conger
	Ophichthidae	*Yirrkala tenuis*	15697	Thin sand-eel
Medium demersal carnivores	Sparidae	*Acanthopagrus berda*	5526	Picnic seabream
	Sparidae	*Acanthopagrus latus*	6356	Yellowfin seabream
	Ambassidae	*Ambassis gymnocephalus*	4806	Bald glassy
	Apistidae	*Apistus carinatus*	6383	Ocellated waspfish
	Apogonidae	*Apogon fleurieu*	4838	Cardinalfish
	Ariommatidae	*Ariomma dollfusi*	60525	
	Soleidae	*Aseraggodes sinusarabici*	58956	
	Bothidae	*Bothus myriaster*	1322	Indo-Pacific oval flounder
	Bothidae	*Bothus tricirrhitus*	58972	
	Soleidae	*Brachirus orientalis*	8312	Oriental sole
	Callionymidae	*Callionymus filamentosus*	225	Blotchfin dragonet
	Callionymidae	*Callionymus gardineri*	1318	Longtail dragonet
	Synanceiidae	*Choridactylus multibarbus*	6387	Orangebanded stingfish
	Gobiesocidae	*Chorisochismus dentex*	23222	Rocksucker
	Cynoglossidae	*Cynoglossus dollfusi*	9250	
	Cynoglossidae	*Cynoglossus gilchristi*	7681	Ripplefin tonguesole
	Cynoglossidae	*Cynoglossus kopsii*	7647	Shortheaded tonguesole
	Cynoglossidae	*Cynoglossus lachneri*	7682	Lachner's tonguesole
	Cynoglossidae	*Cynoglossus lingua*	8238	Long tongue sole
	Cynoglossidae	*Cynoglossus pottii*	56480	
	Cynoglossidae	*Cynoglossus sealarki*	17158	
	Dactylopteridae	*Dactyloptena peterseni*	7691	Starry flying gurnard
	Syngnathidae	*Dunckerocampus boylei*	54745	Broad-banded Pipefish
	Bothidae	*Engyprosopon maldivensis*	13970	Olive wide-eyed flounder
	Platycephalidae	*Grammoplites suppositus*	28128	Spotfin flathead
	Muraenidae	*Gymnothorax herrei*	7491	
	Tripterygiidae	*Helcogramma obtusirostre*	8046	Hotlips triplefin
	Congridae	*Heteroconger balteatus*	55140	
	Narcinidae	*Heteronarce bentuviai*	53919	Elat electric ray
	Syngnathidae	*Hippichthys cyanospilus*	7728	Blue-spotted pipefish
	Syngnathidae	*Hippichthys spicifer*	7495	Bellybarred pipefish
	Syngnathidae	*Hippocampus fuscus*	25955	Sea pony
	Syngnathidae	*Hippocampus jayakari*	53814	Jayakar's seahorse
	Syngnathidae	*Hippocampus lichtensteinii*	53909	Lichtenstein's Seahorse
	Malacanthidae	*Hoplolatilus oreni*	15379	
	Leiognathidae	*Leiognathus fasciatus*	4452	Striped ponyfish
	Triglidae	*Lepidotrigla bispinosa*	28127	Bullhorn gurnard
	Liparidae	*Liparis fishelsoni*	58827	
	Syngnathidae	*Lissocampus bannwarthi*	46165	

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	Synanceiidae	*Minous monodactylus*	6388	Grey stingfish
	Ophichthidae	*Myrophis microchir*	22602	
	Nemipteridae	*Nemipterus bipunctatus*	5851	Delagoa threadfin bream
	Nemipteridae	*Nemipterus peronii*	4554	Notchedfin threadfin bream
	Nemipteridae	*Nemipterus randalli*	5852	Randall's threadfin bream
	Nemipteridae	*Nemipterus zysron*	5855	Slender threadfin bream
	Pinguipedidae	*Parapercis robinsoni*	7867	Smallscale grubfish
	Pinguipedidae	*Parapercis simulata*	56473	
	Pinguipedidae	*Parapercis somaliensis*	10297	Somali sandperch
	Nemipteridae	*Parascolopsis aspinosa*	5856	Smooth dwarf monocle bream
	Nemipteridae	*Parascolopsis eriomma*	5858	Rosy dwarf monocle bream
	Nemipteridae	*Parascolopsis inermis*	5860	Unarmed dwarf monocle bream
	Nemipteridae	*Parascolopsis townsendi*	5859	Scaly dwarf monocle bream
	Pempheridae	*Pempheris mangula*	25449	Black-edged sweeper
	Polynemidae	*Polydactylus plebeius*	7901	Striped threadfin
	Polynemidae	*Polydactylus sextarius*	4470	Blackspot threadfin
	Haemulidae	*Pomadasys punctulatus*	46379	Lined grunt
	Priacanthidae	*Priacanthus sagittarius*	9913	Arrow bulleye
	Paralichthyidae	*Pseudorhombus elevatus*	1333	Deep flounder
	Labridae	*Pteragogus pelycus*	8023	Sideburn wrasse
	Platycephalidae	*Rogadius asper*	8305	Olive-tailed flathead
	Platycephalidae	*Rogadius prionotus*	7897	Blackblotch flathead
	Samaridae	*Samaris cristatus*	8290	Cockatoo righteye flounder
	Holocentridae	*Sargocentron marisrubri*	5347	
	Serranidae	*Serranus cabrilla*	1353	Comber
	Ophidiidae	*Sirembo jerdoni*	10527	Brown-banded cusk-eel
	Ophichthidae	*Skythrenchelys lentiginosa*	59468	
	Soleidae	*Solea elongata*	14394	Elongate sole
	Soleidae	*Synaptura commersonnii*	14395	Commerson's sole
	Syngnathidae	*Syngnathus safina*	61282	
	Batrachoididae	*Thalassothia cirrhosa*	6390	Toadfish
	Syngnathidae	*Trachyrhamphus longirostris*	23124	
	Trichonotidae	*Trichonotus nikii*	27323	
	Mullidae	*Upeneus pori*	46375	Por's goatfish
	Mullidae	*Upeneus sulphureus*	4445	Sulphur goatfish
	Uranoscopidae	*Uranoscopus dollfusi*	46424	Dollfus' stargazer
	Uranoscopidae	*Uranoscopus guttatus*	56494	
	Muraenidae	*Uropterygius genie*	47872	
	Muraenidae	*Uropterygius golanii*	50765	
	Labridae	*Xyrichtys bimaculatus*	14342	Two-spot razorfish
	Labridae	*Xyrichtys javanicus*	56499	
	Labridae	*Xyrichtys niger*	8444	
	Soleidae	*Zebrias quagga*	8194	Fringefin zebra sole
Small demersal carnivores	Ambassidae	*Ambassis urotaenia*	9235	Banded-tail glassy perchlet
	Gobiidae	*Amblyeleotris triguttata*	26636	Triplespot shrimpgoby
	Gobiidae	*Amblygobius magnusi*	56463	
	Gobiidae	*Amoya signata*	17033	Tusk goby
	Caproidae	*Antigonia indica*	59052	
	Apogonidae	*Apogon gularis*	56481	
	Apogonidae	*Apogon hungi*	56482	
	Apogonidae	*Apogon micromaculatus*	56483	

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	Apogonidae	*Apogon quadrifasciatus*	53017	Twostripe cardinal
	Apogonidae	*Apogon smithi*	59514	Smith's cardinalfish
	Apogonidae	*Apogon spongicolus*	56484	
	Scorpaenidae	*Brachypterois serrulata*	9203	
	Callionymidae	*Callionymus bentuviai*	56496	
	Callionymidae	*Callionymus erythraeus*	46382	Smallhead dragonet
	Callionymidae	*Callionymus marleyi*	7650	Sand dragonet
	Callionymidae	*Callionymus muscatensis*	46387	Muscat dragonet
	Callionymidae	*Callionymus oxycephalus*	56498	
	Gobiidae	*Callogobius amikami*	26993	
	Gobiidae	*Callogobius dori*	56134	
	Gobiidae	*Callogobius flavobrunneus*	17050	Slimy goby
	Apogonidae	*Cheilodipterus novemstriatus*	12629	Indian Ocean twospot cardinalfish
	Apogonidae	*Cheilodipterus pygmaios*	12881	
	Pseudochromidae	*Chlidichthys auratus*	56486	
	Pseudochromidae	*Chlidichthys rubiceps*	56487	
	Pomacentridae	*Chromis axillaris*	11854	Grey chromis
	Aploactinidae	*Cocotropus steinitzi*	56490	
	Gobiidae	*Coryogalops anomolus*	46394	Anomolous goby
	Gobiidae	*Cryptocentroides arabicus*	46397	Arabian goby
	Callionymidae	*Diplogrammus infulatus*	17029	Sawspine dragonet
	Callionymidae	*Diplogrammus randalli*	49452	
	Bothidae	*Engyprosopon hureaui*	15567	Hureau's flounder
	Bothidae	*Engyprosopon latifrons*	15569	
	Bothidae	*Engyprosopon macrolepis*	5344	
	Tripterygiidae	*Enneapterygius clarkae*	16975	Barred triplefin
	Tripterygiidae	*Enneapterygius obscurus*	25377	
	Tripterygiidae	*Enneapterygius pusillus*	16979	Highcrest triplefin
	Gobiidae	*Favonigobius reichei*	9945	Indo-Pacific tropical sand goby
	Gobiidae	*Fusigobius humeralis*	59445	
	Gobiidae	*Fusigobius maximus*	59446	
	Gobiidae	*Gobius koseirensis*	61336	
	Gobiidae	*Gobius leucomelas*	61337	
	Gobiidae	*Hetereleotris diademata*	56465	
	Gobiidae	*Hetereleotris vulgaris*	46402	Common goby
	Gobiidae	*Isthmogobius baliurus*	52799	
	Kraemeriidae	*Kraemeria nudum*	60799	
	Leiognathidae	*Leiognathus berbis*	7748	Berber ponyfish
	Leiognathidae	*Leiognathus klunzingeri*	27024	
	Leiognathidae	*Leiognathus leuciscus*	4453	Whipfin ponyfish
	Leiognathidae	*Leiognathus lineolatus*	4563	Ornate ponyfish
	Gobiesocidae	*Lepadichthys erythraeus*	55729	
	Triglidae	*Lepidotrigla spiloptera*	10366	Spotwing gurnard
	Creediidae	*Limnichthys nitidus*	16931	Sand submarine
	Synanceiidae	*Minous coccineus*	10726	Onestick stingfish
	Synanceiidae	*Minous inermis*	46368	Alcock's scorpionfish
	Pomacentridae	*Neopomacentrus taeniurus*	5705	Freshwater demoiselle
	Ophidiidae	*Ophidion smithi*	16788	
	Gobiidae	*Opua elati*	56467	
	Blenniidae	*Parablennius cyclops*	56471	

Group	Family	Scientific name	FishBase Code	FishBase common name
	Microdesmidae	*Paragunnellichthys springeri*	56470	
	Plesiopidae	*Plesiops mystaxus*	27000	Moustache longfin
	Gobiidae	*Pleurosicya prognatha*	56468	
	Gobiidae	*Pomatoschistus marmoratus*	9191	Marbled goby
	Gobiidae	*Psilogobius randalli*	59404	
	Aploactinidae	*Ptarmus gallus*	52867	
	Microdesmidae	*Ptereleotris arabica*	4374	
	Scorpaenidae	*Scorpaenodes steinitzi*	56488	
	Leiognathidae	*Secutor insidiator*	4455	Pugnose ponyfish
	Leiognathidae	*Secutor ruconius*	4811	Deep pugnose ponyfish
	Gobiidae	*Silhouettea aegyptia*	56197	
	Gobiidae	*Silhouettea chaimi*	56469	
	Gobiidae	*Silhouettea insinuans*	9996	Phantom goby
	Syngnathidae	*Siokunichthys herrei*	7190	
	Apogonidae	*Siphamia permutata*	56485	
	Opistognathidae	*Stalix davidsheni*	56472	
	Labridae	*Suezichthys caudavittatus*	4409	Spottail wrasse
	Labridae	*Suezichthys russelli*	4413	Russell's wrasse
	Synanceiidae	*Synanceia nana*	12085	Red Sea stonefish
	Callionymidae	*Synchiropus sechellensis*	25699	
	Syngnathidae	*Syngnathus macrophthalmus*	46212	
	Gobiidae	*Trimma filamentosus*	28064	
	Tetrarogidae	*Vespicula bottae*	56489	
Demersal omnivores	Blenniidae	*Alloblennius pictus*	52391	
	Blenniidae	*Antennablennius adenensis*	46412	Aden blenny
	Blenniidae	*Antennablennius australis*	8042	Moustached rockskipper
	Blenniidae	*Antennablennius hypenetes*	46413	Arabian blenny
	Monacanthidae	*Brachaluteres baueri*	54554	
	Mugilidae	*Chelon macrolepis*	4816	Largescale mullet
	Sparidae	*Crenidens crenidens*	7931	Karenteen seabream
	Tripterygiidae	*Enneapterygius destai*	56507	
	Leiognathidae	*Leiognathus bindus*	4449	Orangefin ponyfish
	Leiognathidae	*Leiognathus elongatus*	4450	Slender ponyfish
	Leiognathidae	*Leiognathus splendens*	4454	Splendid ponyfish
	Mugilidae	*Liza subviridis*	4819	Greenback mullet
	Blenniidae	*Omobranchus fasciolatus*	8038	Arab blenny
	Blenniidae	*Omobranchus steinitzi*	59659	
	Monacanthidae	*Paraluteres arqat*	54621	
	Monacanthidae	*Paramonacanthus frenatus*	8059	Wedgetail filefish
	Monacanthidae	*Paramonacanthus oblongus*	53239	Hair-finned filefish
	Monacanthidae	*Paramonacanthus pusillus*	54624	
	Blenniidae	*Petroscirtes ancylodon*	46423	Arabian fangblenny
	Monacanthidae	*Stephanolepis diaspros*	14343	Reticulated leatherjacket
Demersal herbivores	Blenniidae	*Alticus kirkii*	46411	Kirk's blenny
	Blenniidae	*Alticus saliens*	6031	Leaping blenny
	Cyprinodontidae	*Aphanius dispar dispar*	4813	

Group	Family	Scientific name	FishBase Code	FishBase common name
	Blenniidae	*Ecsenius dentex*	27295	
	Blenniidae	*Entomacrodus epalzeocheilos*	22835	Fringelip rockskipper
	Blenniidae	*Hirculops cornifer*	16944	Highbrow rockskipper
	Blenniidae	*Istiblennius flaviumbrinus*	27245	
	Blenniidae	*Istiblennius pox*	27015	Scarface rockskipper
	Blenniidae	*Istiblennius unicolor*	25453	Pallid rockskipper
	Mugilidae	*Liza tade*	4820	Tade mullet
	Mugilidae	*Valamugil cunnesius*	4700	Longarm mullet
Bentho-	Apogonidae	*Apogon queketti*	8011	Spotfin cardinal
pelagic	Sciaenidae	*Argyrosomus regius*	418	Meagre
fish	Ariommatidae	*Ariomma brevimanus*	10513	
	Ateleopodidae	*Ateleopus natalensis*	10662	
	Syngnathidae	*Bryx analicarens*	46105	Pink pipefish
	Balistidae	*Canthidermis macrolepis*	46433	Large-scale triggerfish
	Carangidae	*Decapterus russelli*	374	Indian scad
	Gerreidae	*Gerres methueni*	7700	Striped silver biddy
	Trachichthyidae	*Hoplostethus mediterraneus mediterraneus*	4964	Mediterranean slimehead
	Sparidae	*Lithognathus mormyrus*	706	Striped seabream
	Lobotidae	*Lobotes surinamensis*	1077	Atlantic tripletail
	Mugilidae	*Mugil cephalus*	785	Flathead mullet
	Salmonidae	*Oncorhynchus mykiss*	239	Rainbow trout
	Moridae	*Physiculus sudanensis*	60891	
	Haemulidae	*Pomadasys striatus*	7301	Striped grunter
	Lutjanidae	*Pristipomoides filamentosus*	201	Crimson jobfish
	Lutjanidae	*Pristipomoides sieboldii*	209	Lavender jobfish
	Carangidae	*Seriola lalandi*	382	Yellowtail amberjack
	Opistognathidae	*Stalix histrio*	23505	
	Stromateidae	*Stromateus fiatola*	1198	Blue butterfish
	Synodontidae	*Synodus randalli*	58509	
	Bramidae	*Taractichthys steindachneri*	3561	Sickle pomfret
	Trichiuridae	*Tentoriceps cristatus*	7947	Crested hairtail
	Terapontidae	*Terapon puta*	7946	Small-scaled terapon
	Gempylidae	*Thyrsitoides marleyi*	7698	Black snoek
	Trichiuridae	*Trichiurus lepturus*	1288	Largehead hairtail
Bathy-	Stomiidae	*Astronesthes martensii*	10213	
pelagic	Sciaenidae	*Atrobucca geniae*	15959	
fish	Myctophidae	*Benthosema pterotum*	10238	Skinnycheek lanternfish
	Champsodontidae	*Champsodon capensis*	10296	Gaper
	Stomiidae	*Chauliodus sloani*	1786	Sloane's viperfish
	Paralepididae	*Lestrolepis luetkeni*	27423	Naked barracuda
	Sternoptychidae	*Maurolicus mucronatus*	51615	
	Nemichthyidae	*Nemichthys scolopaceus*	2660	Slender snipe eel
	Stomiidae	*Stomias affinis*	10167	Günther's boafish
Bathy-	Acropomatidae	*Acropoma japonicum*	1267	Glowbelly
demersal	Congridae	*Ariosoma mauritianum*	7671	Blunt-tooth conger
fish	Bothidae	*Arnoglossus marisrubri*	60532	
	Percophidae	*Bembrops caudimacula*	23546	

Group	Family	Scientific name	FishBase Code	FishBase common name
	Champsodontidae	*Champsodon omanensis*	15604	
	Cynoglossidae	*Cynoglossus acutirostris*	10204	Sharpnose tonguesole
	Synaphobranchidae	*Dysomma fuscoventralis*	15591	
	Nettastomatidae	*Facciolella karreri*	58715	
	Bythitidae	*Grammonus robustus*	15659	
	Synodontidae	*Harpadon erythraeus*	15605	
	Syngnathidae	*Hippocampus kelloggi*	53815	Great seahorse
	Ophidiidae	*Neobythites stefanovi*	15598	
	Tetrarogidae	*Neocentropogon mesedai*	61244	
	Scorpaenidae	*Neomerinthe bathyperimensis*	61433	
	Gobiidae	*Obliquogobius turkayi*	56466	
	Nemipteridae	*Parascolopsis baranesi*	15368	
	Moridae	*Physiculus marisrubri*	15597	
	Gobiidae	*Priolepis goldshmidtae*	59388	
	Congridae	*Rhynchoconger trewavasae*	57764	
	Nettastomatidae	*Saurenchelys meteori*	58724	
	Setarchidae	*Setarches guentheri*	5029	Deepwater scorpionfish
	Acropomatidae	*Synagrops philippinensis*	10338	
	Trichiuridae	*Trichiurus auriga*	8666	Pearly hairtail
	Mullidae	*Upeneus davidaromi*	60913	
	Uranoscopidae	*Uranoscopus marisrubri*	56495	
	Congridae	*Uroconger erythraeus*	15590	

Table E. 2 Key data on fish groups of the Red Sea ecosystem model.

Group No.	Group name	No. of spp.	Trophic level		L∞ (cm)	
			Min	Max	Min	Max
10	Whale shark	1	3.55	3.55	1683.0	1683.0
12	Rays	17	3.1	4.5	68.4	347.4
13	Reef top predators	122	3.98	4.5	9.5	421.1
14	Large reef carnivores	86	3	3.98	51.4	315.8
15	Medium reef carnivores	218	3	3.98	15.0	48.9
16	Small reef carnivores	209	3	3.98	2.1	14.8
17	Reef omnivores	87	2.02	2.99	3.1	115.8
18	Reef herbivores	39	2	2	5.8	94.7
19	Large pelagic carnivores	12	3.47	4.58	105.3	350.5
20	Small pelagic carnivores	35	3	4.5	7.3	87.2
21	Pelagic omnivores	5	2.1	2.95	6.4	26.3
22	Demersal top predators	15	4	4.45	20.6	263.2
23	Large demersal carnivores	24	3.02	3.97	50.1	88.2
24	Medium demersal carnivores	82	3	3.95	15.4	48.4
25	Small demersal carnivores	81	3	3.68	1.8	14.7
26	Demersal omnivores	20	2.45	2.99	3.3	72.3
27	Demersal herbivores	11	2	2.04	6.2	51.5
28	Benthopelagic fish	26	2.13	4.45	3.9	210.5
29	Bathypelagic fish	9	3.03	4.5	4.4	100.0
30	Bathydemersal fish	26	3	4.43	8.5	68.6

E.1.1 Non-fish taxa groups included in the model

Cetaceans

This group includes the dolphins and whales of the Red Sea, whose list and distributions have been described in the literature (Schmitz and Lavigne, 1984; Frazier *et al.*, 1987; Notarbartolo di Sciara, 2002). All the reported cetaceans are from the suborder Odontocetea (toothed whales) except *Balaenoptera edeni* (Eden's whale) and *Megaptera novaeangliae* (humpback whale), which are from the suborder Mysticeti. The P/B values for cetaceans were calculated assuming r/2 (Schmitz and Lavigne, 1984), where r is the average intrinsic rate of growth (0.088 $year^{-1}$) for the Red Sea cetaceans species *Stenella attenuate, S. longirostris, S. coeruleoalba* and *Tursiops truncatus* for which data were available. The estimated P/B for the group equals 0.044 $year^{-1}$. The r/2 method is commonly used to measure P/B of marine mammals (Guénette, 2005;

Ainsworth *et al.*, 2007). The Q/B value was estimated based on the body weight of Red Sea cetaceans taken from Schmitz and Lavigne (1984) and Trites and Pauly (1998), from which the ration was determined using the relationship in Trites and Heise (1996). The average Q/B value, 5.91 $year^{-1}$ was used in the model. Biomass data were not available and were estimated by the model.

Dugongs

Dugongs are herbivore marine mammals whose abundance in the Red Sea is estimated to be 4000 animals (Gladstone *et al.*, 2003). With an average weight of 320 kg (Frazier *et al.*, 1987), the biomass is calculated to be 0.00292 $t{\cdot}km^2$. Similar to the cetaceans, P/B for dugong was calculated using the intrinsic growth rate which is estimated to be 5 % $year^{-1}$ (Marsh *et al.*, 1997), with P/B = 0.025 $year^{-1}$. The Q/B ratio is taken to be 11 $year^{-1}$ as calculated by Ainsworth *et al.*, (2007) based on body weight.

Birds

The sea birds covering the whole Red Sea are described in Evans (1987) and recent reviews on the status of the Red Sea birds by country are available (PERSGA/GEF, 2003; Marchi *et al.*, 2009). However, they are very brief with some list of species sighted and habitat distribution with no estimate of abundance. The P/B value of 0.38 $year^{-1}$ was used based on Russell (1999). Seabird biomass was not available, and was estimated by the model.

Turtles

Five species of sea turtles, hawksbill (*Eretmochelys imbricata*), green (*Chelonia mydas*), loggerhead (*Caretta caretta*), olive ridley (*Lepidochelys olivacea*) and leatherback (*Dermochelys coriacea*), are reported for the Red Sea (Frazier *et al.*, 1987; Tesfamichael, 1994). The first two are the most abundant, with known records of nesting on the Red Sea beaches (Frazier and Salas, 1984; Frazier *et al.*, 1987; Gladstone *et al.*, 2003). The P/B value for turtles was estimated using the relationship $M = -\ln S$, where M is an estimate of P/B and S is the survival rate, which was 0.948 $year^{-1}$ for green turtle (Mortimer *et al.*, 2000) and 0.867 $year^{-1}$ for loggerhead (Chaloupka and Limpus, 2002). This gives an average P/B value of 0.1 $year^{-1}$. P/B value for all turtles in the Caribbean reef was calculated to be 0.2 $year^{-1}$ (Opitz, 1996). Since the P/B estimate using survival rate was only for two species, i.e., it does not include all the five species in the Red Sea, an average of the P/B calculated from survival and the Caribbean value, 0.15 $year^{-1}$, was used for the model. Q/B value of 3.5 $year^{-1}$ was used based on ecosystem models of the Caribbean reef (Opitz, 1996) and west coast of Peninsular Malaysia (Alias, 2003). Sea turtle biomass was not available and was estimated by the model.

Invertebrates

The main invertebrate important for the Red Sea fisheries is shrimp where 64,007 t (14% of total retained trawl fishery) were fished from 1950 – 2006 (see Chapter 4). Hence, shrimps were given a separate functional group. The most common species caught are *Penaeus semisulcatus, P. monodon, Marsupenaeus japonicas, Melicertus latisulcatus, Metapenaeus monoceros and Fenneropenaeus indicus*. P/B value of 5 $year^{-1}$ and Q/B of 29 $year^{-1}$ based on Buchary (1999) were used as a starting parameters to balance the model.

The coral reef structure in the Red Sea is important ecologically and is also the main fishing ground for the artisanal fisheries. Thus, the reef forming corals are categorized as a separate functional group. The high and relatively stable temperature of the Red Sea is favourable for the formation of coral reefs. They are home to more than 200 species of corals (Head, 1987a). The Red Sea coral reef coverage area is estimated to be around 16030 km^2 (Spalding *et al.*, 2001). Coral reefs are more developed in the northern part starting from the tip of Sinai Peninsula going south parallel to the coast until the central part (Sheppard *et al.*, 1992). The longest continuous fringing reef in the Red Sea extends from Gubal, at the mouth of the Gulf of Suez, to Halaib, at the Egyptian border with Sudan (Pilcher and Alsuhaibany, 2000). In the south, more patchy reefs are observed as the turbid water of the shallow shelf does not allow the growth of extensive reefs. Sanganeb Atoll, located in Sudan near the border with Egypt, is the only atoll in the Red Sea. It is unique reef rising from 800 m depth to form an atoll that has been recognized as regionally important conservation area. It was proposed to UNESCO for World Heritage Status in the 1980s (Pilcher and Alsuhaibany, 2000). The biomass of corals was calculated based on data from the southern Red Sea (Ateweberhan, 2004; Tsehaye, 2007) adjusted for the total area of the Red Sea and the north-south abundance gradient giving 2.75 $t \cdot km^{-2}$. The P/B value of corals was calculated based on daily turnover rate of 0.003 day^{-1} (Crossland *et al.*, 1991), which equals to 1.095 year^{-1}. A Q/B value of 9 year^{-1} was used based on the Caribbean reef model (Opitz, 1996).

The other invertebrates included in the model are: non-coral sessile fauna such as sponges, sea anemones, and tunicates; cephalopods: squids, octopuses and cuttlefish; other molluscs; echinoderms: starfish, sea urchins and sea cucumber; crustaceans: representing all crustaceans except shrimps (which have a group of their own); and meiobenthos: polychaetes and nematodes. The P/B and Q/B values of these groups were taken from an ecosystem model of the Eritrean coral reef (Tsehaye, 2007) adjusted for the area of the Red Sea fine tuned during balancing and time series fitting (Table E.3).

Table E. 3 Input parameters of some invertebrates groups.

	Biomass (t·km^{2})	P/B (year^{-1})	Q/B (year^{-1})
Other sessile fauna	0.85	3.2	12
Cephalopods	0.399	3.5	12
Molluscs	0.368	9	30
Echinoderms	0.596	1.6	8
Crustaceans	0.816	3	10
Meiobenthos	0.295	26	100
Zooplankton*	14	52	178

* modified after (van Couwelaar, 1997)

Primary producers

There are three functional groups of primary producers in the model: phytoplankton, sea grasses and algae. The phytoplankton biomass of 21.5 t·km^{-2} and a P/B 110 year^{-1} were used based on data in (Weikert, 1987; Veldhuis *et al.*, 1997) averaged over all the Red Sea. For sea grass, a biomass of 11 t·km^{-2} and P/B value of 19 year^{-1} were used, based on Wahbeh (1988) and Aleem (1979). The biomass estimate of algae was based on Ateweberhan (2004) and Walker (1987), and was averaged for the whole Red Sea, resulting in 38 t·km^{-2}. The P/B value of 14 year^{-1} was used based on Ateweberhan (2004) and Wolanski (2001), which is similar to the value in other coral reef ecosystems: Caribbean (Opitz, 1996) and Indonesia (Ainsworth *et al.*, 2007).

Table E. 4 Diet composition matrix of Red Sea model.

	Prey \ Predator	1	2	3	4	5		7	8
1	Cetaceans								
2	Dungongs								
3	Birds								
4	Turtles								
5	Trawler fishes							0.002	
6	Purse seine fishes	0.010		0.020			0.004	0.002	
7	Beach seine fishes	0.013		0.059			0.151	0.005	
8	Handlining fishes						0.002		0.001
9	Gillnet fishes	0.004		0.001			0.003		
10	Whale shark								
11	Sharks								
12	Rays								
13	Reef top predators					0.011		0.001	
14	Large reef carnivores					0.010	0.003	0.001	0.005
15	Medium reef carnivores	0.013		0.106		0.020	0.001	0.001	0.052
16	Small reef carnivores	0.066		0.271		0.112	0.060	0.015	0.262
17	Reef omnivores	0.131		0.217		0.112	0.060	0.015	0.152
18	Reef herbivores	0.010		0.026		0.112	0.060	0.020	0.202
19	Large pelagic carnivores	0.053		0.020			0.006	0.002	
20	Small pelagic carnivores	0.065		0.180			0.127	0.111	
21	Pelagic omnivores	0.008					0.040	0.015	
22	Demersal top predators								
23	Large demersal carnivores					0.000	0.001		
24	Medium demersal carnivores					0.011	0.006	0.006	
25	Small demersal carnivores	0.131				0.011	0.006	0.006	
26	Demersal omnivores	0.026				0.017	0.006	0.006	
27	Demersal herbivores	0.026				0.020	0.006	0.006	
28	Benthopelagic fish	0.131				0.001			
29	Bathypelagic fish								
30	Bathydemersal fish								
31	Shrimp				0.010	0.010			
32	Cephalopods	0.169				0.112	0.050	0.020	0.011
33	Echinoderms			0.020	0.100	0.057			0.009
34	Crustaceans				0.148	0.226	0.110	0.020	0.197
35	Molluscs				0.015	0.057			0.065
36	Meiobenthos								
37	Corals								
38	Other sessile fauna			0.047	0.233				
39	Zooplankton	0.131			0.070		0.197	0.522	0.001
40	Phytoplankton						0.100	0.180	
41	Sea grass		1.000		0.230				
42	Algae				0.137				
43	Detritus	0.012		0.033	0.056	0.101		0.044	0.043

	Prey \ Predator	1	2	3	4	5	6	7	8
1	Cetaceans								
2	Dungongs								
3	Birds								
4	Turtles								
5	Trawler fishes							0.002	
6	Purse seine fishes	0.010		0.020			0.004	0.002	
7	Beach seine fishes	0.013		0.059			0.151	0.005	
8	Handlining fishes						0.002		0.001
9	Gillnet fishes	0.004		0.001			0.003		
10	Whale shark								
11	Sharks								
12	Rays								
13	Reef top predators					0.011		0.001	
14	Large reef carnivores					0.010	0.003	0.001	0.005
15	Medium reef carnivores	0.013		0.106		0.020	0.001	0.001	0.052
16	Small reef carnivores	0.066		0.271		0.112	0.060	0.015	0.262
17	Reef omnivores	0.131		0.217		0.112	0.060	0.015	0.152
18	Reef herbivores	0.010		0.026		0.112	0.060	0.020	0.202
19	Large pelagic carnivores	0.053		0.020			0.006	0.002	
20	Small pelagic carnivores	0.065		0.180			0.127	0.111	
21	Pelagic omnivores	0.008					0.040	0.015	
22	Demersal top predators								
23	Large demersal carnivores					0.000	0.001		
24	Medium demersal carnivores					0.011	0.006	0.006	
25	Small demersal carnivores	0.131				0.011	0.006	0.006	
26	Demersal omnivores	0.026				0.017	0.006	0.006	
27	Demersal herbivores	0.026				0.020	0.006	0.006	
28	Benthopelagic fish	0.131				0.001			
29	Bathypelagic fish								
30	Bathydemersal fish								
31	Shrimp				0.010	0.010			
32	Cephalopods	0.169				0.112	0.050	0.020	0.011
33	Echinoderms			0.020	0.100	0.057			0.009
34	Crustaceans				0.148	0.226	0.110	0.020	0.197
35	Molluscs				0.015	0.057			0.065
36	Meiobenthos								
37	Corals								
38	Other sessile fauna			0.047	0.233				
39	Zooplankton	0.131			0.070		0.197	0.522	0.001
40	Phytoplankton						0.100	0.180	
41	Sea grass		1.000		0.230				
42	Algae				0.137				
43	Detritus	0.012		0.033	0.056	0.101		0.044	0.043

	9	10	11	12	13	14	15	16	17	18	19
1			0.002								
2											
3			0.002								
4			0.034								
5			0.004		0.003	0.002	0.002		0.000		
6	0.030	0.008	0.004		0.002	0.004	0.004		0.001		0.005
7	0.114	0.005	0.003		0.002	0.002	0.002		0.000		0.015
8	0.003		0.011		0.007	0.008	0.007		0.001		
9	0.002		0.009		0.003	0.003	0.002				0.001
10			0.002								
11			0.005								
12			0.010								
13	0.002		0.004				0.001				0.011
14	0.011		0.090		0.069		0.003	0.003	0.001		0.002
15	0.015	0.022	0.124		0.072	0.055	0.004	0.001	0.003		0.006
16	0.015	0.020	0.131		0.278	0.163	0.186	0.003	0.009		0.018
17	0.015	0.163	0.168		0.154	0.159	0.128	0.012	0.009		0.018
18	0.015	0.009			0.154	0.202	0.151	0.028	0.040		0.011
19	0.020		0.113			0.003	0.002				0.021
20	0.459	0.041	0.113			0.002	0.001				0.236
21	0.088	0.001	0.008			0.000	0.000				0.085
22	0.002		0.024			0.003	0.002				
23	0.001		0.004		0.000	0.000	0.000				
24	0.006		0.006		0.003	0.003	0.002				
25	0.006		0.005		0.003	0.003	0.002	0.076			
26	0.006		0.004	0.021	0.003	0.003	0.002	0.090			
27	0.006		0.002	0.021	0.003	0.003	0.002	0.080			
28	0.003		0.024								0.021
29			0.004								
30			0.002								
31	0.015		0.004	0.014	0.007	0.010	0.005	0.002	0.001		
32	0.045	0.170	0.024	0.004	0.007	0.014	0.012	0.008	0.009		0.276
33	0.031			0.150	0.007	0.004	0.026	0.033	0.028		0.003
34	0.076		0.002	0.088	0.215	0.242	0.051	0.100	0.050		0.224
35	0.003		0.002	0.229	0.007	0.068	0.091	0.047	0.041		0.011
36				0.229		0.007	0.064	0.151	0.041		
37							0.104	0.176	0.070		
38			0.004	0.023			0.042	0.022	0.043		
39		0.366		0.023		0.014	0.062	0.151	0.405		0.015
40		0.184							0.100	0.049	
41										0.098	
42									0.073	0.804	
43	0.010	0.012	0.051	0.198		0.022	0.038	0.015	0.074	0.049	0.020

	20	21	22	23	24	25	26	27	28	29	30
1											
2											
3											
4											
5			0.010	0.010	0.010	0.010			0.015	0.010	
6	0.001										
7	0.037	0.005									
8											
9	0.001	0.000									
10											
11											
12			0.006								
13											
14	0.001										
15	0.001										
16	0.001										
17	0.001										
18	0.001										
19		0.006								0.037	
20	0.081	0.003								0.019	
21	0.154	0.010							0.030	0.007	
22			0.011								
23			0.114	0.002		0.000					0.002
24			0.128	0.100	0.013	0.002			0.040		0.023
25			0.138	0.105	0.136	0.020			0.090		0.023
26			0.142	0.105	0.090	0.114			0.082		0.023
27			0.150	0.105	0.092	0.170	0.060		0.082		0.023
28	0.110		0.061	0.041					0.010		0.010
29										0.012	
30										0.100	0.057
31			0.013	0.052	0.005	0.001	0.001				0.010
32	0.020	0.005	0.049	0.106	0.005					0.142	
33	0.004		0.049	0.052	0.051	0.020	0.020			0.040	0.154
34	0.030	0.081	0.061	0.105	0.136	0.091	0.015		0.100	0.200	0.107
35	0.012	0.020	0.049	0.010	0.068	0.019	0.012		0.082	0.142	0.309
36			0.003	0.052	0.082	0.090	0.039				0.005
37				0.035	0.051	0.060	0.005				
38			0.003	0.017	0.056	0.200	0.002		0.015		
39	0.545	0.417				0.010			0.012		
40		0.402					0.071		0.114		
41							0.014	0.140	0.008		
42		0.025					0.400	0.460	0.020		0.030
43		0.025	0.013	0.102	0.204	0.192	0.360	0.400	0.300	0.290	0.225

	31	32	33	34	35	36	37	38	39
1									
2									
3									
4									
5									
6									
7		0.012							
8									
9									
10									
11									
12									
13									
14									
15									
16									
17		0.012		0.001					
18		0.017		0.001					
19									
20		0.012							
21		0.022							
22									
23									
24									
25		0.005							
26		0.005							
27									
28		0.005							
29									
30									
31	0.005								
32	0.004	0.040		0.002					
33	0.016	0.005	0.009	0.009	0.009				
34	0.001	0.068	0.003	0.001	0.001				
35	0.020	0.100	0.037	0.011	0.010				
36	0.010	0.091	0.030	0.041	0.013	0.015			
37			0.008	0.002	0.003	0.001			
38	0.008		0.004	0.001	0.002	0.000			
39	0.012	0.356		0.101	0.007	0.047	0.250	0.250	0.100
40		0.047		0.078			0.600	0.600	0.900
41	0.118								
42	0.178		0.374	0.114	0.069	0.047			
43	0.628	0.202	0.535	0.638	0.886	0.890	0.150	0.150	

E.1 Ecosim input supplementary data

E.2.1 Reconstruction the fishing effort data of the Red Sea fisheries

Fishing effort is an important part of fishery assessment; however, it is not usually readily available, worse than even catch data. The Red Sea fisheries are divided into two major sectors industrial and artisanal. The industrial fishery has generally better records than the small scale artisanal fisheries. The effort data for the industrial fishery (trawl and purse seine) of the Red Sea was obtained from the database of the Sea Around Us Project (Anticamara *et al.*, 2011; Watson *et al.*, Submitted)

The artisanal fisheries, on the other hand, do not have an effort recording system and the time series effort for the Red Sea fisheries was derived mainly using on the basis of demographic information (fisher numbers), or boat counts. Table (E.5) lists the references from which the effort data were obtained for each country. For Yemen the available data were total number of boats. Egypt has a database system from which the effort data was reconstructed and for Eritrea, because of data availability, the analysis was divided before and after 1991, when Eritrea became an independent nation.

Except for Egypt and Eritrea after 1991, the effort reconstruction procedure was the same. First, an exponential function was fitted to the available effort data, which was then used to predict effort for years it was missing. The exponential function fitted had the form $y = a * e^{b}$; where a and b are constants, presented in Table (E.6) for each country.

Table E. 5 Sources used for the reconstruction of effort of the Red Sea fisheries.

	Effort data			Motorization data		
Country	Year	Data*	Source	Year	%	Source
Sudan	1955	200	Kristjonsson (1956)	1956	1.93	Kristjonsson (1956)
	1976	418	ODA (1983)	1979	22.57	Barrania (1979)
	1979	437	Barrania (1979)	1982	61.98	Chakraborty (1983)
	1981	664	ODA (1983)	2006	95.00	FA (2007)
	1982	605	Chakraborty (1983)			
	2001	743	FA (2007)			
	2006	967	FA (2007)			
Eritrea	1964	3543	Grofit (1971)	1960	1.00	Grofit (1971)
	1968	4167	Grofit (1971)	1963	2.20	Grofit (1971)
	1969	3022	Grofit (1971	1964	3.72	Grofit (1971
	1970	3000	Giudicelli (1984)	1969	42.10	Grofit (1971
	1981	875	Giudicelli (1984)	1974	75.00	Giudicelli (1984)
	1984	250	Giudicelli (1984)			
Yeman	1972	1000	Agger (1976)	1972	10.00	Agger (1976)
	1975	1066	Walczak (1977)	1975	26.45	Walczak (1977)
	1976	1071	Campleman (1977)	1978	60.66	Campleman (1977)
	1978	1597	Campleman (1977)	2006	96.00	MoFW (2010)
	1992	1771	Herrera and Lepere (2005)			
	1997	2686	Brodie *et al.,* (1999)			
	1998	3390	FAO (2002)			
	2000	1781	MoFW (2010)			
	2001	2254	MoFW (2010)			
	2002	2562	MoFW (2010)			
	2003	2737	MoFW (2010)			
	2004	4510	MoFW (2010)			
	2005	5000	MoFW (2010)			
	2006	5727	MoFW (2010)			
Saudi Arabia	1954	2500	Neve and Al-Aiidy (1973)	1955	0.20	Ferrer (1958)
	1971	3250	Neve and Al-Aiidy (1973)	1965	30.77	Neve and Al-Aiidy (1973)
	1980	3678	Barrania *et al.,* (1980)	1969	41.43	Neve and Al-Aiidy (1973)
	1984	2408	Kedidi *et al.,* (1984)	1991	97.00	Sakurai (1998)
	1991	2993	MAW (2008)			
	1992	3443	MAW (2008)			
	1993	3907	MAW (2008)			
	1994	4063	MAW (2008)			
	1995	4316	MAW (2008)			
	1996	4212	MAW (2008)			
	1997	4145	MAW (2008)			
	1998	4209	MAW (2008)			
	1999	4764	MAW (2008)			

Country	Effort data Year	Data*	Source	Motorization data Year	%	Source
	2000	5037	MAW (2008)			
	2001	6116	MAW (2008)			
	2002	6389	MAW (2008)			
	2003	6927	MAW (2008)			
	2004	7266	MAW (2008)			
	2005	6880	MAW (2008)			
	2006	7533	MAW (2008)			

* All effort data are number of fishers except for Yemen, which is number of boats.

Motorization of the fishing vessels affects how effort is calculated significantly, so it was considered explicitly. The rate at which motorization took place in the Red Sea countries was fitted by the logistic curve equation:

$$y = \frac{1}{1 + e^{(\ln a - bx)}}$$

where *ln a* and *b* are constants, which are presented in Table (E.6) for each country

Table E. 6 Parameters of exponential and logistic fitting of effort reconstruction.

	Exponential fitting			logistic fitting		
	a	*b*	R^2	*ln a*	*b*	R^2
Sudan	1.00E-22	0.0287	0.89	275.63	0.1389	0.96
Eritrea	5.00E+106	-0.121	0.92	861.09	0.4369	0.98
Yemen	4.00E-32	0.04	0.78	277.36	0.1399	0.89
Saudi Arabia	9.00E-16	0.022	0.64	487.04	0.2467	0.88

Using the logistic curve fitting results, the total effort was divided into motorized and non-motorized. For the non-motorized effort, number of fishers were converted to horsepower (hp) using the conversion factor one manpower = 0.18 hp/day (Dalzell *et al.*, 1987). For all the four countries, except Yemen, the total effort was given in number of fishers. The total number of boats in the non-motorized category for Yemen was converted to total number of fishers by the average number of fishers per boat (n = 5).

For the motorized part, the horsepower equivalent for each fisher in the motorized boats was first calculated for at least two years in the time series. Two points are needed to account for the change in the hp of the engines installed in the boats over time. Using those points, a time series of hp/fisher was established, which were used to calculate the total hp by multiplying it with the total number of fishers. For Yemen, since the total boats were given instead of total number of fishers, a time series of hp/boat was calculated as a multiplier of the total number of boats. Then the cumulative hp from the non-motorized and that of the motorized effort were added to get the overall total hp for each country.

For Egypt, the calculation was done differently. The artisanal fisheries included in the analysis are what are referred by the Egyptian authorities as 'reef-associated' and 'semi-industrial' (or launch) fishery. Effort data, in total number of trips/landings, was available from 1980 – 2006 (GAFRD, 2010) for the main landing site of Suez for the semi-industrial fishery. First, the number of landing/trips was converted to hp using the average hp/trip calculated from data given in Sanders *et al.*, (1984b). A linear function, was then fitted to the data and used to estimate the effort from 1950 – 1979. The effort from Suez was scaled up to the whole Red Sea using the Suez effort ratio in the whole Red Sea, which was calculated to be 47.7 % (Sanders *et al.*, 1984b). The effort data for Eritrea after 1991 was calculated using effort data available from the Ministry of Fishery (MOF, 2007), which divides it by gear and boat type from 1996 – 2006. For 1992 – 1995, linear interpolation was used to fill the gap.

Subsequently, all efforts were re-expressed in kilowatt-hours. Thus, it was assumed that boats operate 2/3 (243 days) of the year, while for the rest of the year, they are docked for maintenance and/or the fishers are selling their catch or performing other land-based activities. Based on interviews with fishers, an average of 10 hours/day was used to calculate hp.hours from hp.days. Horsepower was converted to watts using the conversion ratio of 1hp = 745.7 watt.

All the major artisanal fishers are included in this analysis, but there are minor fisheries which are not. So, only 90% of the total effort calculated was used in the analysis. The remaining 10%, which was not included, is the effort spent for the minor fisheries. The final stage of the effort reconstruction is dividing total effort into gears. This was done using effort information from the sources presented in Table (E.5). For Sudan, all the effort is used for handlining, because it is pretty much the only gear used by the artisanal fishers. For Eritrea, the composition changed over time from beach seine being dominant in the early years to handlining being dominant in the later years (Figure E.1). For Yemen, first the effort for the least important of the major fisheries, beach seine, was calculated by allocating 10% of the effort in 1950. The effort for the rest of the time was calculated proportionally to the population size and the 1950 data. This is reasonable because beach seine is carried out by people in their localities pre-dominantly for their own consumption; it is the least commercialized fishery. So, I assumed, as the population grows, more and more people are involved in the fishery. The remaining effort was divided 70% for gillnet and 30% for handlining. Yemen has a dominant gillnet fishery whereas the other countries are dominated by handlining. For Saudi Arabia, the effort was divided 70% handlining and 30% gillnet. The total effort for the whole Red Sea by gear type was calculated by adding total efforts of the same gear from all the Red Sea countries (Table E.7)

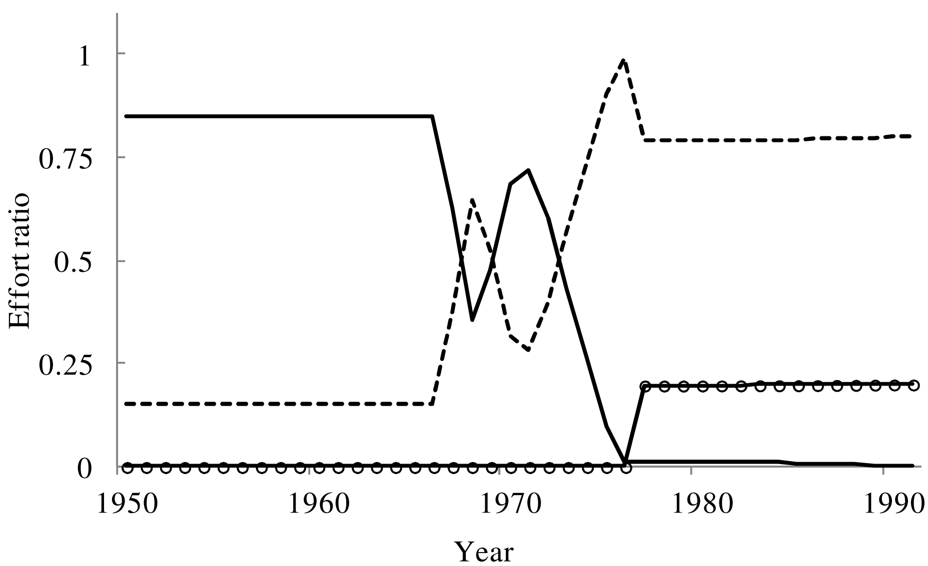

Figure E. 1 Ratios of beach seine (full line), handlining (broken line) and gillnet (line with circles) fisheries in the Eritrean artisanal fishery effort allocation from 1950 – 1991.

Table E. 7 Reconstructed effort of Red Sea fisheries by gear type from 1950-2006.

	Effort (kilowatt.hours)				
Year	Beach seine	Gillnet	Handlining	Purse seine	Trawl
1950	3260163	2409164	5506687	122247	1685304
1951	3261646	2478914	5631296	153416	2010420
1952	3263347	2550989	5758717	152412	2396194
1953	3265170	2625647	5889065	153022	2486810
1954	3267117	2703097	6022413	189598	2633673
1955	3265557	2792947	6175856	185090	2753224
1956	3267845	2878727	6327502	184876	2842540
1957	2906275	2968792	6415349	200680	2625311
1958	2586142	3063659	6515860	207646	2771840
1959	2302782	3163932	6628825	237638	2676854
1960	2052021	3270385	6754326	131544	1542295
1961	1830176	3383946	6892765	136918	1617308
1962	1633982	3505746	7044914	133406	1634785
1963	1547353	3637240	7227335	145992	1874036
1964	1541115	3780044	7436921	146457	1858988
1965	1639968	3936025	7680376	375787	2276185
1966	1874024	4107317	7965751	429322	2408709
1967	1698521	4296088	8875907	418719	2402342
1968	1253924	4504499	10294204	479157	2977451
1969	2070943	4734683	10679160	291247	2244378
1970	3633916	4988745	10483532	283388	2469150
1971	4557226	5325151	11111007	253944	2525112
1972	4391027	6017858	13512905	299842	2509215
1973	3515606	6879881	16761498	310256	2510686
1974	2330559	7927032	20442238	476401	3259823
1975	969981	9168813	24444877	414977	3195146
1976	226857	10605296	28017197	487028	3338693
1977	227999	14923601	29883329	790741	3902215
1978	229451	18027390	34001708	333317	2921845
1979	232530	21624492	38502704	781688	4367463
1980	233061	25751504	43659249	533880	3498433
1981	243346	30438437	49390693	992719	5165161
1982	239757	35737595	55144940	304570	2874781
1983	236236	41674966	61550744	213003	3461937
1984	232767	48285591	68425327	296883	3722514
1985	229389	55602881	75773910	295036	3740346
1986	229581	63655847	83602553	312653	3340348
1987	229020	72475883	91921930	340611	3320155
1988	223816	82090575	100744526	563564	3634536

	Effort (kilowatt.hours)				
Year	Beach seine	Gillnet	Handlining	Purse seine	Trawl
1989	223996	92514901	110082153	728561	3304907
1990	224544	103772729	119952344	727433	3516169
1991	243948	115874916	130359461	722734	3711930
1992	257200	129457088	142265035	909693	3930491
1993	264943	143725688	154935802	838570	4382493
1994	275326	158905420	168173310	695858	6669252
1995	305033	175009249	181984519	724406	6344746
1996	317172	191560732	196924712	820456	8639737
1997	325100	212058648	214737143	1109682	8730950
1998	337872	230889840	230875197	1426178	10096325
1999	349180	252378357	250997094	2103248	13445928
2000	360541	274450818	270357983	1992639	12963567
2001	374877	292928692	283670425	2494183	14137305
2002	387660	316286259	305417442	2815688	14396368
2003	400572	340375293	309461472	2525939	14079268
2004	413612	366520099	338014037	2963705	15941449
2005	426779	395004639	352666794	3032281	16652515
2006	444458	423651161	374812480	3726970	26874663

Table E. 8 Flow parameter (vulnerabilities) for the Red Sea model.

	Prey \ Predator	1	2	3	4	5	6	7	8	9	10
1	Cetaceans										
2	Dungongs										
3	Birds										
4	Turtles										
5	Trawler fishes							3.25			
6	Purse seine fishes	1.01		1.01			1	1.01		1.01	1.01
7	Beach seine fishes	2.26		2			2	3.25		1.01	2
8	Handlining fishes						1		12	7.65	
9	Gillnet fishes	2.26		2			2			2	
10	Whale shark										
11	Sharks										
12	Rays										
13	Reef top predators					2.26		3.25		7.65	
14	Large reef carnivores					2.26	20	3.25	12	7.65	
15	Medium reef carnivores	2.26		2		2.26	20	3.25	12	7.65	2
16	Small reef carnivores	2.26		2		2.26	20	3.25	12	7.65	2
17	Reef omnivores	2.26		2		2.26	20	3.25	12	7.65	2
18	Reef herbivores	2.26		2		2.26	20	3.25	12	7.65	2
19	Large pelagic carnivores	2.26		2			20	3.25		7.65	
20	Small pelagic carnivores	2.26		2			20	3.25		7.65	2
21	Pelagic omnivores	2.26					20	3.25		7.65	2
22	Demersal top predators									7.65	
23	Large demersal carnivores					2.26	20			7.65	
24	Medium demersal carnivores					2.26	20	3.25		7.65	
25	Small demersal carnivores	2.26				2.26	20	3.25		7.65	
26	Demersal omnivores	2.26				2.26	20	3.25		7.65	
27	Demersal herbivores	2.26				2.26	20	3.25		7.65	
28	Benthopelagic fish	2.26				2.26				7.65	
29	Bathypelagic fish										
30	Bathydemersal fish										
31	Shrimp				2.26	2.26				1.5	
32	Cephalopods	2.26				2.26	20	3.25	12	7.65	2
33	Echinoderms			2	2.26	2.26			12	7.65	
34	Crustaceans				2.26	2.26	20	3.25	12	7.65	
35	Molluscs				2.26	2.26			12	7.65	
36	Meiobenthos										
37	Corals										
38	Other sessile fauna			2	2.26						
39	Zooplankton	2.26			2.26		20	3.25	12		2
40	Phytoplankton						20	3.25			2
41	Sea grass		2		2.26						
42	Algae				2.26						
43	Detritus	2		2	2.26	2.26		3.25	12	2	2

	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	3													
2														
3	3													
4	3													
5	3		2	2.26	3.25		3.25					2	2	2
6	1.01		1.01	1.01	1.01		1.01		1.01	1.01				
7	3		2	2.26	3.25		3.25		2	2.26	3.25			
8	3		2	2.26	2.5		2.5							
9	2.5		2	2.26	3.25				2	2.26	3.25			
10	3													
11	1													
12	3											2		
13	3				3.25				2					
14	3		2		3.25	2	3.25		2	2.26				
15	3		2	2.26	3.25	2	3.25		2	2.26				
16	3		2	2.26	3.25	2	3.25		2	2.26				
17	3		2	2.26	3.25	2	3.25		2	2.26				
18			2	2.26	3.25	2	3.25		2	2.26				
19	3			2.26	3.25				2		3.25			
20	3			2.26	3.25				2	2.26	3.25			
21	3			2.26	3.25				2	2.26	3.25			
22	3			2.26	3.25							2		
23	3		2	2.26	3.25							2	2	
24	3		2	2.26	3.25							2	2	2
25	3		2	2.26	3.25	2						2	2	2
26	3	2	2	2.26	3.25	2						2	2	2
27	3	2	2	2.26	3.25	2						2	2	2
28	3								2	2.26		2	2	
29	3													
30	3													
31	3	2	2	2.26	3.25	2	3.25					2	2	2
32	3	2	2	2.26	3.25	2	3.25		2	2.26	3.25	2	2	2
33		2	2	2.26	3.25	2	3.25		2	2.26		2	2	2
34	3	2	2	2.26	3.25	2	3.25		2	2.26	3.25	2	2	2
35	3	2	2	2.26	3.25	2	3.25		2	2.26	3.25	2	2	2
36		2		2.26	3.25	2	3.25					2	2	2
37					3.25	2	3.25						2	2
38	3	2			3.25	2	3.25					2	2	2
39		2		2.26	3.25	2	3.25		2	2.26	3.25			
40							3.25	2			3.25			
41								2						
42							3.25	2			3.25			
43	3	2		2.26	3.25	2	3.25	2	2		3.25	2	2	2

	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
1															
2															
3															
4															
5	2			2	2										
6															
7								2							
8															
9															
10															
11															
12															
13															
14															
15															
16															
17								2		2					
18								2		2					
19					2										
20					2			2							
21				2	2			2							
22															
23	2					2									
24	2			2		2									
25	2			2		2		2							
26	2			2		2		2							
27	2	2		2		2									
28				2		2		2							
29					2										
30					2	2									
31	2	2				2	15								
32					2		15	2		2					
33	2	2			2	2	15	2	2	2	2				
34	2	2		2	2	2	15	2	2	2	2				
35	2	2		2	2	2	15	2	2	2	2				
36	2	2				2	15	2	2	2	2	2			
37	2	2							2	2	2	2			
38	2	2		2			15		2	2	2	2			
39	2			2			15	2		2	2	2	2	2	2
40		2		2				2		2			2	2	2
41		2	2	2			15								
42		2	2	2		2	15		2	2	2	2			
43	2	2	2	2	2	2	15	2	2	2	2	2	2	2	

Table E. 9 Feeding rate parameters for the Red Sea model.

Group	Max rel. feeding time	Feeding time adjust rate [0,1]	Group	Max rel. feeding time	Feeding time adjust rate [0,1]
Cetaceans	2	0.5	Pelagic omnivores	2	0.5
Dungongs	2	0.5	Demersal top predators	2	0.5
Birds	2	0.5	Large demersal carnivores	2	0.5
Turtles	2	0.5	Medium demersal carnivores	2	0.5
Trawler fishes	2	0	Small demersal carnivores	2	0.5
Purse seine fishes	2	0	Demersal omnivores	2	0.5
Beach seine fishes	2	0	Demersal herbivores	2	0.5
Handlining fishes	2	0	Benthopelagic fish	2	0.5
Gillnet fishes	2	0	Bathypelagic fish	2	0.5
Whale shark	2	0.5	Bathydemersal fish	2	0.5
Sharks	2	0	Shrimp	2	0
Rays	2	0.5	Cephalopods	2	0.5
Reef top predators	2	0.5	Echinoderms	2	0.5
Large reef carnivores	2	0.5	Crustaceans	2	0.5
Medium reef carnivores	2	0.5	Molluscs	2	0.5
Small reef carnivores	2	0.5	Meiobenthos	2	0.5
Reef omnivores	2	0.5	Corals	2	0.5
Reef herbivores	2	0.5	Other sessile fauna	2	0.5
Large pelagic carnivores	2	0.5	Zooplankton	2	0.5
Small pelagic carnivores	2	0.5			