MARINE EXTINCTIONS - PATTERNS AND PROCESSES

EXECUTIVE SUMMARY

This synthesis, sketched during the course of the meeting, was developed in the following months on the basis of further inputs received by the participants, under the coordination of Ferdinando Boero, James Carlton and Frédéric Briand. The latter reviewed and edited the entire volume, whose physical production was carried out by Valérie Gollino.

1. INTRODUCTION

The study of extinction in the sea is fraught with challenges. On the one hand species long thought extinct are re-discovered or otherwise “resurrected” on a regular basis (Keith and Burgman, 2004; Scheffers et al., 2011). On the other hand, it seems probable that many species believed to still exist in our oceans may have long since gone extinct. Further, a robust understanding of the processes that may be currently driving species to, and over, the extinction cliff, often remains elusive, especially for those species where obtaining rigorous population and distribution estimates is expensive, arduous and problematic.

To cast a light on the current processes and extent of marine extinctions, CIESM invited a selected group of 16 specialists from various disciplines – ranging from marine biology, community dynamics, population genetics, paleontology, fishery science, historical ecology and evolution (see list at end of volume). They were welcomed in the futuristic Center of Arts and Sciences of Valencia by CIESM Director General, Dr Frédéric Briand, who started by thanking Dr Daniel Garcia Parraga for hosting this 45th Workshop of the Commission in ‘his’ splendid Oceanogràfic building, collaborator Dr Paula Moschella for her efforts in the logistic preparation, and last but not least Dr Ferdinando Boero, Chair of CIESM Committee on marine ecosystems, for suggesting this exciting, timely theme and for agreeing to act as discussion moderator/stimulator.

In his opening remarks, Frédéric Briand focused on a number of issues and open questions which the four-day exploratory meeting would explore in earnest, such as the proximate/ultimate causes of extinction, the spatio-temporal scale of the process, the relevance or not of rarity, the available evidence from past extinction events, the tools and models available to assess the current rates of extinction, the risks of a sixth forthcoming wave of extinction, and appropriate conservation measures to reduce man’s acceleration of the process. Ferdinando Boero followed, highlighting the difficulty of securing reliable, quantitative data on a scientific question so elusive as biodiversity changes in the vast marine realm, before inviting participants to present their paper.

Red vs black lists
Species particularly vulnerable to human impacts raise most concern about mass extinction. A great deal indeed of recent published works has addressed the potential for habitat destruction,
water quality degradation, overfishing, climate change, and other processes to push species to the brink (Pew Oceans Commission, 2003). While there are enduring, long-term challenges in determining the threatened, endangered, and extinct status of terrestrial and freshwater species (Scheffers et al., 2011), these challenges are vastly more exacerbated in the world’s oceans.

**Species lists**

Naming species is probably the first form of culture, and it is even written in the Genesis that “the Creator brought animals to the first human to see what name he would have given to them”. The task of naming species is still unfinished. Estimates say that about two million species have been named, and that there are almost six or more millions that are still unnamed. Some scientists even estimated how many of these unknown species are becoming extinct before we are even aware of their existence. Strange enough, it is presumed that unknown species are becoming extinct, while there is little proof that the known ones are really extinct!

**The inventory of the natural capital**

Producing a rigorous catalogue of threatened, endangered, or extinct species is a challenge in the absence of detailed knowledge of regional marine biota. Few such thorough inventories exist, and no inventories are known to us that accurately reflect the current knowledge of systematics, distribution, biology (including life cycles), and ecology (such as the place in a trophic network) of all marine species within a region – admittedly a daunting task. Checklists alone do not reveal the population status of the vast majority of species or when they were last seen. For European seas, there is the European Register of Marine Species http://www.marbef.org/data/erms.php, for example, and, broader still, the Ocean Biogeographic Information System (http://www.iobis.org/). For most species on these lists, non-specialists would be surprised to learn that we know little more than their morphology and have only a coarse-grained view of their distribution. If, and where, populations have declined or disappeared for, literally, hundreds of thousands of marine species, is simply not known, a reality which may be obscured by the apparent existence of extensive “data bases” on the world’s marine biodiversity.

**Biodiversity increase: real or artefact?**

The first species lists contained just a small fraction of biodiversity. Species numbers have been growing as long as new species were described or newly recorded for a given place. So, the number of species is in continuous increase. This is happening both globally and locally. The arrival of many non-indigenous species in the Mediterranean, for instance, is leading to a marked increase in the species numbers that are making up the biodiversity of the basin. Some of these species are labelled as “worst aliens” and their presence is considered as negative, although their very presence represents an increase in species numbers. One of the features of these “worst aliens” is their negative impact on native species that should be pushed on the verge of extinction by the newcomers. The newcomers, however, often arrive and become established because of physical conditions changes (e.g., due to global warming) to the detriment of native species that are not tolerant enough to withstand the new situation. Under such circumstances, pre-adapted species to the new conditions might take the place of the original, now “maladapted ones”. In this case the substitution of the native species by the non-native ones merely reflects changing environmental conditions. Whatever the cause, it is anyway important to remain aware of possible extinctions, if only to demonstrate that we are really going through a biodiversity crisis.

This enterprise is possible, and our workshop aimed at showing its feasibility while taking the Mediterranean Sea as a paradigm for the world ocean, and by tackling the problem of extinction both from a paleontological and a neontological point of view, putting in contact fields of expertise that rarely do interact.

**Marine vs terrestrial extinctions**

Concern about extinction is widespread and leaves almost no room for doubt. But if the question is posed about naming extinct species, the first ones that come to mind are usually the dodo and the great auk (not to mention dinosaurs), while names do not come to mind when asked to list extinct marine species. Unfortunately such lists do exist, even though they do not contain “charismatic” species, i.e. the popular animals that are familiar to the public at large. The bias
towards these species is, however, not justified when the problem of extinction is tackled from a scientific point of view.

The number of marine species is much lower than that of terrestrial ones, even if the diversity of body plans (e.g. phyla) is much higher in the sea than on land. The insects, making up almost half of known species, are paradigmatic in this respect, while having relatively few marine representatives. The phyla of the interstitial fauna, for example, are almost exclusively marine and, as such, constitute a great contribution to the diversity of life at higher levels of organization. The lower species diversity of marine life, if compared to terrestrial one, is often explained by the high connectivity characterizing marine environments, with lower chances of population segregation, leading to allopatric speciation. The barriers separating terrestrial habitats have no comparison in the marine realm. Local extinction is of course possible, but the wider distribution of marine species is conducive to the survival of marine forms in other places. Marine extinctions, for these reasons are far more difficult to establish than those affecting terrestrial groups.

Peculiarities of the Mediterranean Sea
After the Messinian crisis, about six million years ago, the Mediterranean biota became established by recolonisation through the strait of Gibraltar. In different geological periods, species with different features entered the basin. Species of cold affinity entered during the cold periods, whereas species of warm affinity entered during warmer periods. Large seasonal fluctuations in temperature allowed for the survival of both contingents, if their life cycles and histories involved periods of activity (during the favourable season) and periods of rest (during the unfavourable one). At present, the Mediterranean biota in surface waters, does have a tropical nature in the summer and a temperate nature in the winter. The Mediterranean is also characterized by a high rate of endemism. The entrance of species is rather easy, near the surface, due to the presence of a surface current entering from the Atlantic. The outgoing current is deeper and surface species might find it difficult to get out, while having good chances of getting in. Under these circumstances, the Mediterranean behaves as a trap that lets species in but prevents them from getting out. This situation is conducive to the high rates of endemism that characterize the Mediterranean Sea biota. These species are liable of extinction due to environmental change and, since they are not present elsewhere, local extinction might be equal to final extinction.

The Mediterranean Sea, thus, is a paradigmatic area to study the impact of environmental change on species survival. This advantage, however, is to be considered with care. The history of marine taxonomy views the Mediterranean as a very important centre, due to the concentration of taxonomic efforts both in the past and in the present. New species, described from the Mediterranean, and thus having this sea as their type locality, might be newcomers that were unknown in their original area of distribution, and were ‘discovered’ by local taxonomists upon their arrival, just as the recently described jellyfish species *Marivagia stellata* and *Rhopilema nomadica*. These species most probably entered in the Mediterranean through the Suez Canal and were non-described in their native area due to lack of taxonomic expertise, soon to be detected once they reached an area “patrolled” by active taxonomists. For taxonomy, the Mediterranean is the type locality of these species, but this does not reflect their actual distribution.

**Rarity**
Most species are poorly known simply because they are inconspicuous and the perception of their existence is based on just a few records, sometimes even just one: the original description. These species are labelled as rare, while this may be simply due to insufficient sampling or lack of expertise. The processes leading to extinction imply a decrease in number, and it seems logical that rare species are in a risky situation, due to the scarcity of their populations. But, since most species are rare, and just a few are abundant at a given period in the history of a biota, rarity is not a risky condition per se. The alternation of periods of abundance and rarity, in fact, might be the main motor of species diversification, through flush and crash phenomena that represent sudden pressures of natural selection on species populations. During the periods of flush, species are represented by a multitude of individuals, but these cannot persist for long, due to the overexploitation they exert on the very resources that should sustain them. The collapse of these populations (the crash) removes maladapted individuals and enhances the surviving ones that
survived just due to genetic makeups conducive to ecological success. In light of these considerations, rarity is not a sufficient precondition to extinction.

2. ASSESSING EXTINCTION – WHAT CAN WE LEARN FROM PALEONTOLOGY?

Patterns seen in the past are becoming increasingly important for predicting the future. This is especially true for marine extinctions, for which the fossil record provides invaluable data on multiple temporal and spatial scales while evidence for modern extinctions comes largely from terrestrial environments. A major limitation of using the fossil record in a straightforward way is its incompleteness and the vast time scales on which global patterns are usually being assessed. The incompleteness and many other issues related to sampling can be overcome by applying rigorous methods of sampling standardization on fossil occurrences combined with appropriate counting methods (Alroy et al., 2001; Alroy, 2008; Alroy et al., 2008). The vast time scales can be used as an advantage because we can observe the fate of fossil lineages from their origin until final extinction. Paleontologists can thus assess extinction rates and their selectivity directly, without relying on inferences of extinction risk as used in the IUCN Red List. In addition, deep time patterns inform us about the natural variability of species abundances (if indirectly) and geographic ranges. In linking taxonomic and ecological information paleontologists can thus evaluate a number of key questions such as:

2.1 Which traits render a species prone to extinction?

The suite of factors that paleontologists have identified is very similar to that offered by neontologists (McKinney, 1997; Kiessling, this volume). Examples are specialization, mode of life, mode of reproduction, and abundance traits. Most of these traits have long been identified as important determinants of extinction risk in a qualitative way, but more recent studies have helped to assess their relative importance. For example, while body size, abundance and geographic range have all been linked to extinction risk, geographic range is the only one of these factors that directly controls extinction risk (Harnik, 2011). The other two factors are only indirectly linked to extinction risk.

As clear from the IUCN Red List, rarity does not necessarily mean enhanced extinction risk because rarity is a natural state for many species (Mace et al., 2008). A recent study using the entire marine fossil record confirmed that among the various forms of rarity low population size has the weakest effect on extinction risk, whereas restricted geographic range is the most important driver followed by narrow habitat breadth (Harnik et al., 2012a,b). Abundance has a U-shaped relationship with extinction risk in fossil marine bivalves. Very rare and very abundant taxa show elevated extinction rates, whereas extinction risk is minimized at intermediate abundances (Simpson and Harnik, 2009). The common notion of specialist species being at greater risk of extinction than generalists holds true, but there are issues with defining what a specialist really is. The fossil record shows that habitat specialists are at a greater risk of extinction but also have greater chances of speciation (Kiessling and Aberhan, 2007a; Colles et al., 2009).

Several additional traits that increase extinction risk in marine animals have been identified, based on fossil invertebrates. An important trait is low metabolic rate and the formation of heavy skeletons, which increased extinction risk during times of massive changes in ocean chemistry such as ocean acidification (Kiessling and Simpson, 2011; Knoll and Fisher, 2011). The general notion that marine animal species are less extinction-prone than terrestrial animal species is supported by the fossil record (McKinney, 1998). However, this does not imply that marine species are less at risk today, because the fossil record also tells us that during mass extinctions marine taxa were hit as hard as terrestrial taxa (Benton, 1995).

2.2 What besides magnitude distinguishes background extinctions from a mass extinction?

Paleontologists have long emphasized the dichotomy between background extinctions and mass extinctions (Jablonski, 1986a). Mass extinctions are defined by extinction magnitudes that are significantly above background extinctions, which declined over the course of the Phanerozoic eon (the last 540 million years) (Kiessling, this volume). There is no arbitrary choice of a proportion of taxa becoming extinct but experience shows that the traditional Big Five mass extinction of the Phanerozoic (Raup and Sepkoski, 1982) wiped out more than 40% of marine genera and probably more than 70% of marine species. Some rules that govern survival during normal times do not
apply during global catastrophes. An important example is geographic range, which facilitates survival during background times but not during mass extinctions (Kiessling and Aberhan, 2007b; Payne and Finnegan, 2007). This is probably due to the global scope of environmental changes that lead to mass extinctions, whereas background extinctions were triggered by biotic interactions and regional environmental change. Other traits governing survival during background times may also become ineffectual during mass extinctions (Jablonski and Raup, 1995) but the selectivity of mass extinctions can be used efficiently to assess their specific causes (Smith and Jeffery, 1998; Kiessling et al., 2007; Knoll et al., 2007). The difference in selective regimes between background and mass extinctions has probably been overemphasized in the past. The question if we are already approaching a mass extinction event (Barnosky et al., 2011) is still important to put the current biodiversity crisis in a geological context, but not crucial to assess extinction risk of extant species with the help of the fossil record.

2.3 What are the natural causes of extinction?

All ancient mass extinctions are associated with massive perturbations of the global carbon cycle and rapid climate change. The ultimate triggers of ancient mass extinctions range from slow processes such as plate tectonics to shock events such as meteorite impacts and are thus very different from the entirely anthropogenic driver today. However, the time scales involved in actually triggering marine extinctions were perhaps not as different as commonly assumed. It is more the failure to resolve the duration of ancient extinctions than factual evidence for prolonged crises that led to the notion of vastly different time scales involved in extinctions now and then. Probabilistic approaches rendered it likely that marine extinctions occurred in pulses, not only during mass extinctions but also during background intervals (Foote, 2005). Rapid climate change is a component of all mass extinctions although the causes and pace of climate change varied considerably. The massive release of greenhouse gases due to volcanism is seen as a crucial trigger of two out of three mass extinctions in the last 250 Myr and the most recent of these (the end-Cretaceous mass extinction) was probably caused by a meteorite impact (see Kiessling, this volume).

2.4 What is the natural variability of population sizes?

Defining natural baselines is among the central tasks of the emerging field of conservation paleobiology (Dietl and Flessa, 2011). What was natural in the coastal oceans (Jackson, 2001) is a key question for which paleo-ecological data can be especially useful. Studies from shallow time are useful to assess natural variations in population size. The purpose of previous studies was largely to monitor economically important or hazardous species over time scales beyond historical records (Walbran et al., 1989; Valdés et al., 2008), to assess changes in productivity (Kowalewski et al., 2000) or to separate invasive from native species (van Leeuwen et al., 2008). Fossil data can enhance our knowledge on the natural variability of population sizes and should thus be included in the assessments of extinction risk for recent species, especially in the marine realm, where knowledge is so poor compared with terrestrial records.
Box 1. Confidence in extinction.

How long must a species go unseen before it can safely be declared extinct? This is a difficult question, which cannot be answered with a simple number that is valid for all species. A conspicuous species that is regularly sighted will need less time to be declared extinct with confidence than an inconspicuous species that is only identified by specialists. Complete certainty on species extinction is virtually impossible to achieve as demonstrated by repeated sightings of presumably extinct species. In the most extreme case, the time span between last sighting and re-discovery can span millions of years as exemplified by the gap of presumed coelacanth extinction in the Late Cretaceous (ca. 80 myr) and the discovery of living *Latimeria* in the 1930s. The problem of when a species should be considered extinct has thus concerned both biologists and palaeontologists (Strauss and Sadler, 1989; Carlton et al., 1999).

Paleontologists have developed tools to quantify the confidence with which a species can be considered extinct. Those models were first applied to stratigraphic sections (Strauss and Sadler, 1989) and later to global taxonomic ranges (Marshall, 1990; Marshall, 1994). Biologists have adopted and further developed these approaches. Current approaches on the temporal distribution of sighting records are rather complex and require advanced statistical knowledge (Solow and Roberts, 2003; Solow, 2005; Collen et al., 2010).

We recommend using an adjusted version of Marshall’s (1990) simple equation as a first approximation for poorly documented marine groups because this can be applied with ease by taxonomists and it does not require information about the temporal distribution of sightings.

The confidence (C) of the declaration of a species being extinct at a given time is calculated by

\[
C = 1 - \left( \frac{G}{R + 1} \right)^{(H-1)}
\]

where

- G = number of years since last sighting
- R = years between first record (the date of first collection) and the last sighting
- H = number of individual years in which there is a record

A species could be declared extinct if the confidence is 95% or greater. An 80% confidence should be be taken as a critical values warranting closer inspection.

This said, we caution that this formula is only applicable to larger well-known species for which it can be demonstrated that both the historical and modern-day record is thorough and rigorous. For most species, data relative to sightings are an artifact of a combination of sampling intensity (either spatially or temporally) with the ability of workers to identify a species. Many species in many community samples simply go unidentified because no taxonomists are available, and thus we have no ability to assess the continued presence, or presumptive absence, of a vast number of species. Thousands and thousands of marine species – especially protists, invertebrates, and smaller algae – have gone unreported for decades or centuries since their first descriptions, simply because no one has sought them out again. As pointed out by Boero (2011) how many inconspicuous species have probably gone in complete indifference? Current knowledge depends on whether anyone has actually sampled or identified these species over subsequent years. The modern-day record demonstrates that even large, once-abundant species (e.g. sharks, see Soldo, this volume) can simply disappear without notice, suggesting that documenting the disappearance of uncommon and smaller species is a fundamental challenge.
3. **PREDICTING RISK OF EXTINCTION**

3.1 Overexploitation

Over-extraction of marine resources, habitat destruction, water quality, climate change and invasive species are together threatening the marine biota and marine ecosystems. Due to rapid coastal urbanization and industrialization, point and non-point source land and urban runoff has rendered what were once natural, diverse estuaries, bays, and lagoons – but are now marinas, busy harbors, and industrial wastelands – nearly biologically depauperate. For many locations we have poor historical data on overfishing / overexploitation, except on hunting of marine species of megafauna. Many populations and species of marine mammals (see Panigada and Pierantonio, this volume), seabirds, and marine turtles are now at a fraction of their former pre-exploitation abundance levels and listed as threatened in the IUCN Red List (Dulvy et al., 2009).

Marine fish and shellfish (including molluscs and crustacean) species have also experienced large reductions in abundance from former levels since medieval times (Hoffmann, 2005), with industrial-scale fisheries commencing in the late 19th and early 20th centuries. The Food and Agriculture Organization of the United Nations (FAO), in charge of collecting world fishery landings statistics and summarizing the status of global fisheries, calculated that in 2009 over 87% of the commercially important fish stocks were already either fully exploited, or overexploited (FAO, 2012). However, the FAO global status assessment covers only a small number of exploited fish resources, leaving out hundreds of species, and thousands of populations for which there are not official statistics, particularly excluding bycatch species and species exploited by artisanal and subsistence fisheries (Zeller and Pauly, 2007).

There have been also multiple attempts to quantify the impacts of fishing on several groups of data-rich species, commonly large predatory fishes, with the objective of providing a more accurate picture of their trajectories and reductions from known historical levels (historical baselines). Hutchings and Reynolds (2004) examined data of 230 marine fish populations in the North Atlantic and estimated a reduction of 83% in adult biomass from known historic levels. The adult biomass of scombrids species (tunas and mackerels) is estimated to have decreased globally on average by 60% since the 1950s, with temperate tuna exhibiting the largest declines in biomass (on average 80% reductions) (Juan-Jorda et al., 2011). Similarly, large pelagic shark populations have declined by more than 75% in the Northwest Atlantic Ocean and over 90% in the Gulf of Mexico (Baum et al., 2003; Baum and Myers, 2004).

Although these global or regional synthesis studies provide a more accurate picture of the biomass trajectories of commercially important fish populations, the reality is that biomass estimates and the current exploitation status for the large majority of fish species are still uncertain or unknown globally. We still rely on the FAO landings fish statistics, rather than population biomass estimates, to illustrate the impacts of fisheries on marine living resources within the last 50-60 years of industrialized fisheries. Global fisheries landings reveal that the average trophic level of the global catch has declined over time, suggesting that predatory fishes have been sequentially declining as fisheries started to also target middle and lower trophic fish species, an indication that both fishing down and through marine food-webs is occurring (Pauly et al., 1998; Essington, 2006).

Long term trends of global fish landings also signal that fish resource are exhaustible. Since the 1980s, fish landing have leveled off (if China statistics are included) or have slowly decreased (if China statistics are excluded), suggesting that food webs are becoming simplified and that it is getting harder to extract fish from the oceans despite all the technological developments (Watson and Pauly, 2001; Pauly et al., 2005). At the same time there is increasing evidence that jellyfish abundance is increasing worldwide (Brotz et al., 2012), and that fishing – by removing the natural predators of jellyfish species – might be in part responsible for this trend (Purcell et al., 2007). The impacts of reducing large amounts of biomass from the oceans and the indirect effects of overfishing on the structure and functioning of marine ecosystems are still poorly understood (Scheffer et al., 2005). One of the best documented cases of cascading effects induced by overfishing is the Canadian cod collapse and its effects all the way down the foodweb (Frank et al., 2005). There is growing evidence that changes at the top of the food chain can provoke sudden
ecosystem changes, sometimes referred to as regime shifts, and that such changes in ecological state may be irreversible once over some tipping points (Casini et al., 2008).

Factors contributing to overfishing
Multiple factors have been identified as main drivers contributing to overfishing, thus jeopardizing the sustainable management of marine ecosystems and increasing the rates of extinction of marine species. The following drivers have been identified as the four largest contributors to overfishing: 1) fish subsidies; 2) overcapacity in fisheries; 3) growing demand and price of marine products; and 4) illegal fishing (Pauly and Alder, 2005; Sumaila et al., 2008; Pauly, 2009). Subsidies, in most cases facilitated by governments, are considered to be the most significant drivers of overfishing. Subsidies typically contribute to the development of bigger and more efficient fleets, increase fishing effort and the net profits of fishers, thus sustaining fishing fleets that otherwise would not be economically viable (Sumaila et al., 2010). Second, the current fleet overcapacity is at least two and a half times greater than required to bring long-term catches at a sustainable rate (Pauly, 2009).

Third, global human population growth connected with an increase in demand and price values of marine products are also contributing to overfishing. Some species can reach high prices in the international markets, creating incentives for overfishing. For example, in 2011 a single Pacific bluefin tuna was sold for more than 400,000$ in Tokyo market. Although the value of this particular fish does not represent the average sale value of bluefin tunas in the global markets, it clearly illustrates the inflated values reached by some fish species, which generate high pressures and incentives for overfishing. Fourth, illegal, unreported and unregulated (IUU) fisheries also fuel the problem of overfishing. It has been estimated that between $10bn and $23.5 bn (between 11 and 26 million tones) are lost annually worldwide due to current illegal and unreported fishing (Agnew et al., 2009). Although there have been some attempts to halt and reduce IUU fisheries, control and surveillance of fisheries worldwide continue to be a challenge.

From collapse to extinction
Although there are numerous examples of marine populations and species that have suffered declines of 80-90% or more from pre-exploitation abundance and numerous examples of fish collapses precipitating closure of fisheries, it has been widely assumed (and still held) that marine species are less vulnerable to fishing exploitation and less prone to extinction than terrestrial species. This assumption arises in part from two reasons. First, few marine species (relative to terrestrial species) have been documented to have become globally extinct in the last century and those now extinct had relatively small ranges (Dulvy et al., 2009). Second, the intrinsic biology of marine species, particularly the biology of teleost fish with large fecundities combined with their widespread distributions and high abundances, has led to the wrong assumption that marine fish species are more resilient to fishing impacts and therefore less vulnerable to extinction than other non-fish marine species or terrestrial species.

Recently these perceptions have been challenged and questioned by many (Hutchings, 2001; Sadovy, 2001; Dulvy et al., 2003). Marine extinctions are now believed to be underestimated because of low detection abilities and the general lack of information of the status of the majority of marine species (Dulvy et al., 2009; Carlton, this volume). There are many examples of local extinctions of marine species and the reporting of local marine extinction is increasing over time. Given that local extinctions are the first step towards global extinction, the importance of local extinctions cannot be underestimated. Large reductions of biomass to very low levels, triggered by overfishing and fragmented habitats caused by destructive fishing methods, are two factors likely to lead to numerous local extinctions, especially in species with the most intrinsic vulnerable life histories, such as the long-lived, slow growing and fragile species (Sadovy and Cheung, 2003). Moreover, the widely-held belief that large fecund fishes are more resilient to overexploitation lacks any scientific support. Instead, there is increasing agreement that highly fecund fishes (largely teleost) are not more resilient to overexploitation or extinctions than terrestrial mammals (Hutchings et al., 2012). There is a need to focus on fragmented populations and populations with low abundance levels induced by fishing. At these stages, the loss of genetic diversity, decompensation (Allee effects) and inbreeding depression in fragmented and small populations might drive species to the brink of extinction (Briggs, 2010).
Besides fishes, several valued benthic invertebrates, such as bath sponges and corals have been subjected to harvesting for centuries by humans (for details see Voultsiadou et al., this volume). The commercial value of such species commonly increases as they become less abundant and this, in turn, leads to even more intensive harvesting and poaching. Thus, they may not necessarily become economically extinct before their local or regional extinction, as is assumed for fish stocks (Dulvy et al., 2003). Moreover, the withdrawal of these organisms can have an increased impact on the benthic marine ecosystem, since they act as ecosystem engineers (Coleman and Williams, 2002) enhancing the complexity of the substratum available to other organisms. Bath sponge and red coral populations are exhibiting a continuously declining trend reaching local extinction in several areas, which demands urgent monitoring and conservation interventions.

One of the best known examples of fish stock collapse is the case of Atlantic northwest cod fishery. This fishery, which existed for more than half of a millennium and shaped the coastal communities of the eastern Canadian cost, was stopped by the Canadian Government in 1992. The Atlantic northwest cod fishery was, for centuries, based on fishing gear used on restricted fishing grounds. Thus, catches were limited, allowing normal reproduction of the cod. From the mid 20th century cod fishery started to be more industrialized in terms of using new technology: dimensions of trawls, and consequently its catchability, were increased; more powerful and bigger trawlers, equipped with radars, sonders and sonars, were used. Use of new technology expanded old fishing grounds, especially to deeper areas, while CPUE, measured by a time of towing and area covered was increased enormously. Huge increase of catches, which during 1970's peaked to 810,000 tons, resulted in partial collapse of the northwest cod fishery. Although the fishery was supervised and managed, the exact state of the cod stock was not recognized at that time as management measures were set, based on defective calculations of maximum sustainable yield. Fishing continued, as the government, responding to pressure from the fishing industry, failed to intervene. An additional problem, not taken into account, was ecological: increase of catches of cod was followed by a huge increase of bycatch, consisting of non-commercial, but ecologically very important fish. The collapse was catastrophic: Atlantic northwest cod stock fell to 1% of earlier biomass level and Canadian government declared a complete moratorium on the cod fishery. More than 40,000 workers from the fishing industry became unemployed and the cod stock has still not recovered.

Due to a lack of management interest for chondrichthyan species, and although these species are much more vulnerable to overfishing (see Soldo, this volume), well-documented cases of chondrichthyan stocks' collapses are rare. Of those, the case of the porbeagle shark fishery – Lamna nasus – is perhaps the best known. In the Northeast Atlantic porbeagle has been fished by the fleets of many European countries. The fishery began when Norway started targeting porbeagle in the 1930s using long lines. Fishery reopened after the Second World War and catches reached a peak of 6,000t in 1947. Although porbeagle was a target species, there has never been any restriction on fishing effort. From 1953 to 1960 the fishery collapsed and resulted in the redirection of fishing effort by Norwegian and Danish long line shark fishing vessels into the Northwest Atlantic. That fishery was only sustained for six years before collapsing in the 1960s. In the Northeast Atlantic current biomass and numbers are showing a decline of 94% and 93%, respectively, while in the Mediterranean Sea, the porbeagle is on the verge of regional extinction, with a calculated population decline of over 99,99% since the 1950s.

**Prey depletion vs direct targeting**

Prey depletion may lead to nutritional stresses for marine vertebrates. Trites and Donnelly (2003) described how marine mammals may respond to systematic lack of food, providing evidence of e.g. reduced birth rates and body size and increased newborn and juvenile mortality. Changes in the behavior have also been described, with animals performing longer feeding dives, together with physiological alterations. Prey depletion may cause a reduction in reproductive rates and this may represent one of the principal factors causing population decline in marine mammals. However, the decline of a population may be caused by a series of effects (see Panigada and Pierantonio, this volume), acting in synergy, and singling out each cause may prove rather difficult.

Intensive and poorly regulated fishing efforts in the Mediterranean Sea (CIESM, 2000; FAO, 2000) may lead to ecological extinctions, caused by the dramatic impact that overfishing has on stocks (e.g. Pauly and Palomares, 2005; Stergiou and Koulouris, 2000) and ecosystems (Jackson et al.,...
Prey depletion, caused by overfishing, is considered as one of the principal causes for the decline of coastal odontocete species, such as the short-beaked common dolphin (*Delphinus delphis*) (Bearzi *et al.*, 2003; Panigada and Pierantonio, this volume).

### Alien species and extinctions

To date no introduced species is known to have caused the extinction of another species in the sea. As noted in this Monograph, however, the record of extinctions is so poorly known that it is risky to assume that non-indigenous species have not led to global extinctions, especially given the vast number of invasions in regions such as the Mediterranean Sea (over 600 species! CIESM, 2001/2002; Galil, 2012) and San Francisco Bay (Cohen and Carlton, 1995). This said, many hundreds of species of non-indigenous protists, invertebrates, algae, and fish have caused the severe decline of many native species (reviewed in part in Rilov and Crooks, 2009), such that celebrating the lack of evidence of global extinction at the hands of invasions is of little comfort. Chapman *et al.* (2012) have detailed an extraordinary example of the arrival of a non-native parasite that has rendered a large marine benthic thalassinid extinct in many bays along the Pacific coast of North America in the past 20 years. While this decapod is not globally extinct, their work serves as a potential harbinger of the full-court press of invasions now underway around the world, and as a model for what may have occurred, unnoticed, in the past.

### Minimum viable population size

The minimum viable population size is the number of individuals under which the population is supposed to become extinct in the wild. It is often defined as the population size necessary to ensure between 90 and 95 percent probability of survival between 100 to 1,000 years. It depends on numerous factors such as the reproduction system of the species (for instance consanguinity is increased for smaller populations), the ecology of the species and the environment variability, and the past history (when a population or a species survived severe past bottlenecks, the consequent inbreeding has more chances to survive in future since it purged its deleterious alleles). This is very difficult to estimate, and requires computer simulations based on demographic and environmental data parameters which need to be obtained by field studies. Most of these influential factors will affect genetic diversity. Consequently population genetics provides very powerful (and indirect) tools to estimate effective sizes of populations and species (see Chenuil, this volume).

### 3.2 What do we need to build reliable models and scenarios?

Metapopulation theory – both from a population genetics and ecological dynamics point of view – is rich in predictions and scenarios. Yet most predictions are largely focused on one level of organization (i.e., genetics or ecology) and remain to be tested (Lande, 1988; Hanski, 2011). This is unfortunate because we are witnessing an explosion of better and more accurate models, high-resolution data, and increasing computer power and storage but all of them remain highly independent in most scientific disciplines (Jones *et al.*, 2006). Thus, common sense suggests that the first thing we need for building reliable models is to join efforts, combine a suite of realistic scenarios with different levels of complexity, high-resolution data and quantitative methods to compare models, and infer the processes that may help us to anticipate species extinction or diversity loss in specific features of natural metapopulations (Beaumont, 2010).

Merging realistic models, high-resolution data and quantitative methods is challenging but it can have useful consequences to train our intuition about extinction processes. For example, results coming from theory suggest that demographic thresholds – critical population values below which the population goes extinct – are particularly relevant to anticipate extinctions (Nee, 1994). These thresholds – highly related to the minimum viable population size (see Chenuil, this volume) – are normally derived after different types of disturbances that reduce the fraction of available patches in a metapopulation context. It has been observed that these thresholds may change with the level of spatial resolution, the complexity of the food web, and the effect of environmental variability acting on networks of patches (Ovaskainen *et al.*, 2002). Changes in the thresholds – as in the minimum viable population size – may also be a function of the shape or the topology of the populations in the spatial landscape, or the life-history traits and these and additional factors make predictions to anticipate an extinction extremely difficult (Hanski and Ovaskainen, 2000).
Currently, the idea of a threshold in metapopulations is quite a general concept but the conditions under which this may occur seem rather context-dependent and taxon-specific. Which highlights the importance of connecting informed theory, using empirical estimations from data across disciplines and taxa. In this regard, concepts like the threshold in a population is helpful to distinguish linear from nonlinear processes or the speed of a population to go extinct.

The vulnerability of a species to extinction is determined by its degree of exposure to extrinsic threats, such as fishing, habitat destruction or climate change, and its intrinsic sensitivity to the threatening process. The intrinsic sensitivity of a species to external threats is determined by the species characteristics, such as life history and ecology, which underlie the productivity of the species and its capacity to recover from known threats. The presumed resilience of marine species to become extinct compared with terrestrial species in contemporary times has been questioned. Given the current exceedingly high extinction rates of species, more than ever there is an increasing need to understand which biological and ecological factors are more likely to determine which species will be able to adapt to current threats and which will go extinct. Moreover, the vulnerabilities of species to extinction are known to vary across marine taxa and across different types of threat, yet the intrinsic taxonomic and ecological correlates of extinction risk remain poorly understood across marine taxa and across different types of threat.

Life history theory suggests that species with ‘slow’ life histories characterized by large longevities, slow growth, late maturation and slow fecundities, should be at greater risk of extinction than species with “fast” life histories characterized with the opposite suite of traits. While there are some empirical studies in marine mammals and fishes testing this hypothesis, empirical testing of this hypothesis lags for the majority of the marine invertebrate groups. The most useful biological predictor of extinction risk in marine fishes is large body size and second in importance, age at maturity. Maximum body size is the most reliable correlate of marine fish species vulnerability to fishing, suggesting that it might be the most reliable predictor of species declines, recoveries and threat status in marine fishes. Age at maturity is the most consistent and reliable biological correlate of species intrinsic sensitivity, suggesting that age at maturity might be the most reliable predictor of marine fish species maximum per-capita growth rates (for details see Juan-Jordá et al., this volume). In marine mammals, larger body mass at weaning, fewer births per year, smaller geographical range sizes, small social groups and the taxonomic group have been identified as the most useful predictors of extinction risk globally. In contrast, the biological and ecological correlates of extinction risk in marine invertebrates are poorly known. More worrying, current risk assessments or the risk status for the majority of invertebrate groups (e.g. echinoids, bivalves, etc.) are lacking or are very uncertain. For invertebrate groups, we rely on the knowledge of the extinction rates in the fossil record, i.e., what paleontologists have identified as the most important biological and ecological factor of extinction risk in the fossil record.

Overexploitation and habitat destruction have been identified as major causes of local and global marine extinctions in the recent and current history. Over the coming century, marine species will be faced with additional threats derived from changes in ocean temperature and changes in ocean chemistry which might interact and intensify the effects of overexploitation and habitat destruction. To date the majority of empirical studies have focused on identifying what life history and ecological traits of species are most useful to predict extinction risk. However, under the effect of current changes in ocean temperature and ocean chemistry, there is an urgent need to undertake comparative studies across taxa to identify what physiological characteristics of the species, such as their thermal tolerance limits and CO₂ tolerance limits, are determinant to predict their capacity to acclimatize and adapt to different scenarios of ocean warming and ocean acidification and thus determine what species might be able to adapt and which species might go extinct.

Genetic diversity, bottlenecks, genetic drift, founder effects. Extinction or adaptation (acclimatation).

Adaptation corresponds to the increase in frequency of genes providing an increased survival and reproduction under prevailing environmental conditions. In the absence of genetic diversity adaptation cannot occur. Furthermore when genetic diversity is low, homozygous genotypes become more frequent including for deleterious recessive alleles (inbreeding depression). Thus the genetic diversity of natural populations, which can be assessed easily and non-invasively, with
molecular markers (Chenuil, 2006), can be used as a proxy to vulnerability, to which it is inversely correlated.

3.3 Genetic warning signals (loss of genes)

When monitoring a population via mere counting of individuals observed in the field, a loss of genetic diversity, thus an increase in vulnerability can be overlooked, because populations can recover after a perturbation although their adaptation potential decreases after each perturbation (Chenuil, this volume).

Frequency of mass mortalities, anoxic crisis

Besides harvesting pressure, mortality from disease is an important ongoing threat for marine populations and can be evaluated as a warning signal of potential local extinction. Several severe incidents have been reported during the past decades (Webster, 2007; Garrabou et al., 2009), affecting mostly sessile invertebrates, such as bath sponges and Anthozoans in the Mediterranean Sea. Mass mortality events have been associated to environmental temperature anomalies that promote stress and consequently chemical and microbial shifts in the affected organisms (Webster et al., 2008; Lejeusne et al., 2010). Thus, they are expected to be more intense and recurring within a reportedly increasing warming trend (Coma et al., 2009). Monitoring disease incidents, especially in the most sensitive areas, e.g. the southeastern Mediterranean, is an urgent priority.

3.4 From local to global extinction

Along with other traits that can cause a higher extinction risk, a geographical range size of certain species is one of the most important. It can be presumed that large and abundant populations with global distribution will not be significantly influenced by local or regional extinctions, but what about a species with small populations and geographically restricted distribution, such as marine mammals and chondrichthyan fish (see Panigada and Pierantonio; Soldo in this volume)? Evidently, the importance of a broad distribution in permitting a large population size, or as a buffer against habitat loss or overfishing, is such that it transcends biological differences among taxonomic groups, as well as differences in the threatening processes among regions (Cardillo et al., 2008). On the other hand, patchy populations (i.e. those with high amounts of dispersal among local populations) are most likely to exhibit an increase in synchrony following extinction.

Numerous species in the wild can be modeled as metapopulations, which are a set of local populations that may undergo local extinction, and that exchange migrants. Population genetics again allows estimating connectivity among demes (local populations), an important parameter related to the risk of global extinction. The risk of local extinction can in some cases be estimated by genetic diversity, but if environmental stochasticity is high and demes small, genetic diversity is of poor use.

4. MANAGEMENT ISSUES (AND RECOMMENDATIONS)

MPAs

Marine Protected Areas (MPAs) have been used as a measure for the protection of endangered species or populations (see Voultsiadou et al., this volume), or of sensitive ecosystems. Additionally, MPAs can contribute to the conservation of representative habitats which support rich diversity (e.g. Mediterranean coralligenous assemblages and Posidonia meadows), nursery grounds and Essential Fish Habitats, as well as undisturbed pristine sites. The latter can recover from or adapt more easily to natural and anthropogenic phenomena, such as the temperature rise, and can be used as reference sites for monitoring relevant unprotected areas. MPAs can also provide spillover effects to the surrounding areas (PISCO, 2011).

In 2010 5,800 MPAs existed globally, covering 1.2% of the ocean, while only 0.1% encompass fully protected no-take Marine Reserves (PISCO, 2011). A major impediment to marine conservation is the ineffective management and surveillance of MPAs: a number of cases are just ‘paper parks’, where no management measures have been implemented (Abdulla et al., 2008). The critical need for the establishment of networks of Marine Reserves, high seas MPAs, and ‘Marine Peace Parks’ globally has been underlined by scientists (Coll et al., 2012), scientific commissions (CIESM, 2011), NGOs (Greenpeace, 2006; OCEANA, 2011), and Conventions (see Giakoumi et al., 2012 for an analytical listing). The 2003 IUCN World Parks Congress goal for
protecting 20-30% of the world’s oceans within representative Networks of MPAs by 2012 has been largely ignored and the Convention on Biological Diversity Meeting in Nagoya (2010) set the target to protect 10% of each coastal and marine ecoregion by 2020.

**Fisheries management (no take areas, nursery areas, spawning areas, quotas)**

Multiple management tools exist to meet combined fisheries and conservation objectives and reach consensus towards sustainable use of marine resources. Quota restrictions, gear modifications, temporal and spatial area closures, no take areas, community management, creation of economic incentives are all examples of traditional management tools that work towards restoring depleted populations, ultimately protecting them from local or global extinctions. Experience has shown that combining diverse management actions can lead to successful management of marine resources, keeping in mind that the best combination of management actions depends on the resource and on the local context.

Large shark monitoring in the Adriatic started in late 1990s by collecting the data from marine police, harbor offices and fishermen. Later, by advertising the monitoring in marine journals and other media, the monitoring was enriched by data compiled by the broader interested public. Currently, it constantly provides data not only on large sharks, which remain the main goal of the monitoring, but also on other marine organisms, especially rare and new species for the Adriatic.

**Remedial actions**

**Better use of fisheries statistics (data)**

Collection of scientific data has a long history. Nowadays most of the data are stored electronically and can be easily available thru web-based datasets such as the Global Biodiversity Information Facility [GBIF, www.gbif.org]. Until recently most of the scientific data were stored in paper format, in local libraries, limiting their dissemination and accessibility. Given the increasing rates of loss in biodiversity and extinction risk globally, it is essential to design strategies to digitally recover historical datasets, particularly the recovery of long-term and large scale historical surveys. Historical data can provide valuable information to construct baselines of species distribution, abundance and biodiversity, which is critical to monitor the extinction rate of species. We recommend and encourage any efforts to recover and restore historical data sets and facilitate their accessibility. Successful projects have shown that the cost of recovering data is a small percentage of the initial project costs. In addition, there have been numerous global strategies to construct global datasets such as the GBIF to encourage free and open access to valuable scientific data. We believe that scientific data should always be easily available and accessible and that a standard practice of any scientific project should be to ensure that no data is lost to future generation of scientists.

**Issue proper legislation and enforce it (no paper parks)**

Marine Protected Areas (MPAs) have been set up to protect vulnerable species and ecosystems, to conserve biodiversity and minimize extinction risk, to re-establish ecosystem integrity, to segregate uses to avoid user conflicts and to enhance the productivity of fish and marine invertebrate populations around a reserve (Pauly et al., 2002; Hooker and Gerber, 2004).

One of the crucial feature making a Marine Protected Area efficient is the establishment, maintenance and economical support of a proper management body. Without appropriate management plans, coupled with enforcement and compliance efforts to ensure that rules are respected and measures are correctly implemented, the risk that the MPA will be perceived only as a “paper park” is more than concrete (Notarbartolo di Sciara, 2008; Reeves, 2000).

Systematic monitoring programs, long-term goals, enforcement policy, public awareness efforts are among the tasks to include in a proper and effective management plan; these objectives should be assessed at regular intervals, to make sure the institutional aims of the Marine Protected Area are addressed and achieved.

**Strengthen ex situ conservation**

As shown in Box 2, much remains to be done to enhance useful synergies between the research community and large public aquaria. While these offer an unequalled showcase for displaying
recent scientific findings to a large audience, they also allow easy access to the animals for non-invasive research, for the study of aging, behaviour, lymphocytes, etc.

Box 2. The potential role of public aquaria for *ex situ* conservation by Daniel García Parraga

<table>
<thead>
<tr>
<th>Research Lines</th>
<th>Potential research inputs of aquarium community to species conservation</th>
<th>Potential scientific community should contribute with large aquaria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offer concrete resources:</td>
<td></td>
<td>Provide knowledge and ideas:</td>
</tr>
<tr>
<td>- Access to animal collection and biological samples otherwise very hard to obtain from nature;</td>
<td>- Assisting in project design and execution. Supervising and guiding the aquarium conservation programs.</td>
<td></td>
</tr>
<tr>
<td>- Access to historic info/data/samples for each animal;</td>
<td>- Giving a scientific basis and format to all knowledge generated and presented.</td>
<td></td>
</tr>
<tr>
<td>- Offering facilities for research;</td>
<td>- Involving aquarium personnel on research execution and diffusion.</td>
<td></td>
</tr>
<tr>
<td>- Offer veterinary expertise;</td>
<td></td>
<td></td>
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<tr>
<td>- Access to other institutions.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diffusion</th>
<th>Provide factual, updated information to the general public. Design strategies or contingency plans for transmission to the public.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuse platform of science for the general public, media, universities and schools: panels, conferences, congresses, scientific events. Raise public awareness.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Funding</th>
<th>Raise funds for conservation research from:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Private companies;</td>
<td>- Official programs;</td>
</tr>
<tr>
<td>- Donations from visitors;</td>
<td>- Private companies.</td>
</tr>
<tr>
<td>- Incomes.</td>
<td></td>
</tr>
</tbody>
</table>

Some success stories

**Marine turtles**

The present status of the Mediterranean population of the loggerhead marine turtle *Caretta caretta*, an endangered species under strict protection (e.g. Barcelona and Bern Conventions, CITES), can serve as an example of effective monitoring and conservation efforts. Extensive research, including beach monitoring, tagging, and public awareness for more than 20 years in the main Mediterranean nesting areas (i.e. the western coast of Greece and Cyprus), has been carried out mostly by environmental organizations (Margaritoulis, 2005). In spite of difficulties due to ineffective enforcement of the legislation and incidental capture of turtles in fishing gear, encouraging trends of populations recovery have been observed in areas where conservation measures are applied (for details see Voultsiadou et al., this volume). Stabilization of population numbers and increase of annual birth rate have been also recorded for the monk seal *Monachus monachus* in the Northern Sporades, Aegean Sea, since monitoring efforts started in the area (see Dendrinos et al., 2007).

**Sharks in Croatia**

Chondrichthians, especially sharks, have suffered huge declines in the Adriatic, as well as in whole Mediterranean area. In the absence of usually required stock assessment data, chondrichthians were simply not managed. Now, Croatia has chosen to apply the precautionary approach to chondrichthyan management, based on existing available data (see Soldo, this volume). As a result, 23 chondrichthyan species (16 of them large sharks, mainly highly migratory species) have been granted strict protected status by Croatia in past five years, the highest level of protection in the country.

**Rebuilding stocks of East Atlantic and Mediterranean bluefin tuna?**

The overexploitation of East Atlantic and Mediterranean bluefin tuna is well documented, reflecting many problems found in the world fisheries, i.e. severe overexploitation driven by high
market value, an open access in international waters where in the absence of control, regulations are easy to ignore. Recent indications of improvement in Atlantic bluefin tuna stock status (Porch and Fromentin, 2013) due to the imposition of strict fishery regulations, following intense mediaic pressure by concerned NGOs, illustrates that despite many sources of uncertainty in the projections of future trends, the management of a heavily exploited fish stock can still show hopes for recovery when there is a strong political will.