FISH and FISHERIES

Fishing groupers towards extinction: a global assessment of threats and extinction risks in a billion dollar fishery

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Abstract

Groupers are a valuable fishery resource of reef ecosystems and are among those species most vulnerable to fishing pressure because of life history characteristics including longevity, late sexual maturation and aggregation spawning. Despite their economic importance, few grouper fisheries are regularly monitored or managed at the species level, and many are reported to be undergoing declines. To identify major threats to groupers, the International Union for Conservation of Nature (IUCN) Red List criteria were applied to all 163 species. Red List assessments show that 20 species (12%) risk extinction if current trends continue, and an additional 22 species (13%) are considered to be Near Threatened. The Caribbean Sea, coastal Brazil and Southeast Asia contain a disproportionate number of Threatened species, while numerous poorly documented and Near Threatened species occur in many regions. In all, 30% of all species are considered to be Data Deficient. Given that the major threat is overfishing, accompanied by a general absence and/or poor application of fishery management, the prognosis for restoration and successful conservation of Threatened species is poor. We believe that few refuges remain for recovery and that key biological processes (e.g. spawning aggregations) continue to be compromised by uncontrolled fishing. Mariculture, through hatchery-rearing, increases production of a few species and contributes to satisfying high market demand, but many such operations depend heavily on wild-caught juveniles with resultant growth and recruitment overfishing. Better management of fishing and other conservation efforts are urgently needed, and we provide examples of possible actions and constraints.

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Introduction

As the world's human population continues to expand, so does the demand for marine food sources and the number of individuals whose livelihoods and sustenance fully or partly depend on marine ecosystems (Garcia and Rosenberg 2010). Among harvested marine species, population declines of as much as 90% have been reported for pelagic fish species (e.g. Myers and Worm 2003), and coastal reef fishes have shown reductions of more than 4% per year since the mid-1990s in some areas (e.g. Paddack *et al.* 2009). For many groups, these declines show little evidence of slowing, and over-harvest is now considered by some to be the major threat to marine populations, more so than habitat loss or degradation (reviewed in Dulvy *et al.* 2003). Even conservative evaluations of threats to marine biodiversity acknowledge that certain groups, such as some sharks, rays and reef-associated species, are particularly vulnerable and seriously reduced from anthropogenic impacts, particularly fishing (del Monte-Luna *et al.* 2007).

The identification of the mechanisms driving extinction risk is therefore of utmost importance to address the 'coral reef crisis' (Bellwood *et al.* 2004), especially for species or species groups of importance to fisheries that may face 'double jeopardy' in the face of large-scale environmental change. Understanding major drivers of threats for particular taxa is important for being proactive; fish populations may become harder and more expensive to restore as they become smaller and more impacted because of phenomena like depensation or increased management costs.

Globally, landings of marine fishes are not uniform; a few fish groups dominate catches because of various factors including natural abundance, consumer preference, geography, history and ease of catch. Examples include cods (Gadidae), tunas and mackerels (Scombridae) and anchovies (Engraulidae; http://www.fao.org/fishery/sofia/en accessed 14 November 2011). In areas with coral reef ecosystems, a diversity of species is harvested worldwide in both commercial and small-scale, multi-species fisheries. The latter often represent the predominant fishery, employ a wide range of traditional and advanced fishing techniques and are important to millions of fishers for food security and livelihoods (Salas *et al.* 2007; Garcia and Rosenberg 2010). Common representatives of fish landed in these fisheries include the snappers (Lutjanidae), surgeonfishes and unicornfishes (Acanthuridae), parrotfishes (Labridae), emperor breams (Lethrinidae) and groupers (Epinephelidae). The latter group, in particular, represents an assemblage of species that is often heavily exploited, is among the highest priced market reef species, is highly regarded for the quality of their flesh, and this is often among the first coral reef fish groups to be overexploited (Sadovy 1994; Chiappone *et al.* 2000). The implications of losing grouper fisheries, therefore, are severe for many coastal communities and ecosystems.

According to the Food and Agricultural Organization of the United Nations (FAO), groupers contributed more than 275 000 tonnes to global capture fisheries production in 2009 (http://www.fao.org). This represents an increase of nearly 25% from the previous decade (approximately 214 000 tonnes in 1999) and is more than 17 times the capture production reported in 1950 of approximately 16 000 tonnes (Fig. 1). Assuming an average weight of 3 kg per fish landed [certainly an overestimate, e.g. in Indonesia Pet and Pet-Soede (1999) estimated 1.3 kg for cyanide fishing, and in Hong Kong markets juveniles below 1 kg comprise over 80% of fish by number among the most commonly retailed groupers (To and Sadovy de Mitcheson 2009)], the total catch volume translates to at least 90 000 000 groupers taken in 2009. While this trend of increasing catches reflects growing demand and intensification of fishing effort for these valuable species, it also substantially underestimates true landings primarily because of the unreported catch within the many small-scale, multi-species fisheries involved (e.g. Sadovy *et al.* 2003; Sadovy 2005; Zeller *et al.* 2005).

Of the total grouper production in 2008, more than 80% was reported from Asia. Although these FAO data certainly under-represent total landings from the region, the heavy signal from Asia is likely to reflect a real trend. The disproportionate geographic contribution highlights several factors, including increasing human population size in Asia which in turn leads to growing seafood demand and numbers of fishers, as well as changing trends in marine resource use. Additionally, there is an ever-growing number of source countries providing fish for the Chinese market, all typically occurring in the absence of fishery management. One example of the latter is the emergence of a large international trade in luxury seafood items, including the live reef food fish trade (LRFFT) which accounts for a significant proportion of the grouper trade in the region (Sadovy *et al.* 2003). In this market, consumers are able to select a fish displayed alive prior to cooking, and this has become a driving force in both the capture and demise of a number of grouper populations in parts of Southeast Asia and the western Pacific (Sadovy *et al.* 2003; Warren-Rhodes *et al.* 2003). With a market valued at almost US $1 billion per year and accounting for nearly 20% of the reported global grouper catch, the LRFFT has virtually extirpated some species from areas nearest to its trade centre in Hong Kong, forcing suppliers to seek fish from ever distant localities (Fig. 2).

In addition to the obvious importance of groupers to global fisheries, this group of fishes is important

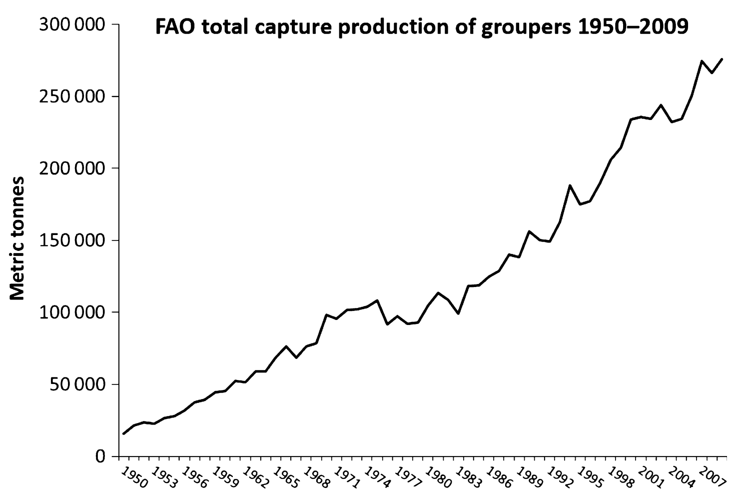

Figure 1 Food and Agricultural Organization of the United Nations (FAO) capture production landings data for groupers 1950–2009.

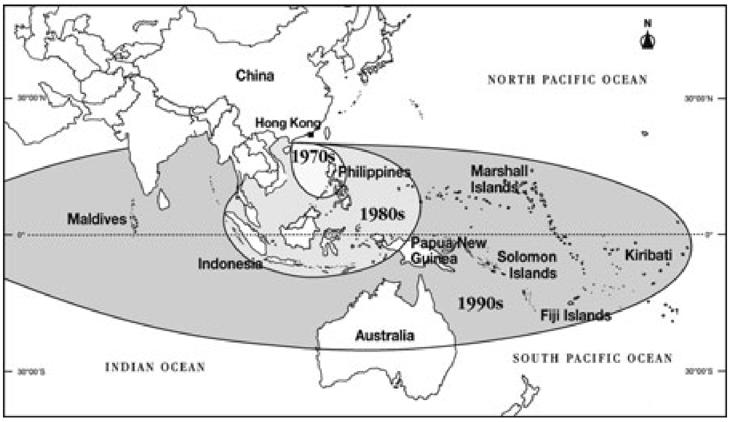

Figure 2 Expanding trade in the live reef fish food trade from Hong Kong (from Sadovy *et al.* 2003 with permission).

to marine ecosystems. Groupers are ubiquitous predators and, with many reaching sizes of 1 metre or more in length, may play a large role in moderating the abundance of prey species (Hixon and Carr 1997; Stewart and Jones 2001). Some groupers also have physical effects on habitat through burrowing and excavation behaviour (Coleman *et al.* 2010). While many of the potential effects on marine ecosystems have yet to be quantitatively documented, it is apparent that the importance of this group to reef ecosystems from an ecological perspective cannot be underestimated.

The International Union for Conservation of Nature (IUCN) Species Survival Commission is composed of numerous specialist groups (SG) that are distinguished by taxonomic (e.g. Salmon) or functional (e.g. Sustainable Use) units. Each specialist group is responsible for evaluating their particular group of organisms at the species level in terms of their risk of extinction based on IUCN's widely recognized and respected categories and criteria (Rodrigues *et al.* 2006; Mace *et al.* 2008). Many SGs are also heavily involved in conservation work. Numerous taxa have been evaluated for extinction risk, and two recent reviews have highlighted these risks for groups that provide the foundation for marine ecosystems worldwide [e.g. corals (Carpenter *et al.* 2008) and seagrasses (Short *et al.* 2011)]. The enormous economic value of grouper fisheries and their importance for livelihoods and food security provided impetus for compiling the data presented here.

Following the inclusion of several groupers and the Napoleon (or Humphead) wrasse (*Cheilinus undulatus;* Labridae) on the IUCN Red List in 1996, and in response to a growing concern that rising fishery pressure on these two taxonomic groups (Epinephelidae and Labridae) was causing irreparable harm to the population stability of several species; the Groupers & Wrasses Specialist Group (GWSG; http://www.iucn.org/about/work/programmes/species/about_ssc/specialist_groups/directory_specialist_groups/directory_sg_fishes/groupers_wrasses_sg/, accessed 14 November 2011) was formed in 1998. Red List assessments of many species of high commercial importance were completed after the group formed, and the remaining groupers were assessed in a workshop setting in Hong Kong in February 2007.

Herein, we present the results of over 10 years of assessments for all groupers worldwide and show that 20 species (12% of all grouper species) are at risk of extinction if current trends continue, with an additional 22 species (13% of all grouper species) considered Near Threatened. We show that certain areas of the world contain a disproportionate number of Threatened species, while others contain a disproportionate number of poorly documented and Near Threatened species in need of critical biological study. We also examine trends in body size and biological characteristics in relation to conservation status among the groupers. Additionally, we demonstrate that extinction risk in groupers is largely driven by fishing pressure. As a whole at least, one quarter of all known grouper species will face economic, if not ecological and biological, extinction or local extirpation in the near to medium future if current population trends and the general lack of fishery management in coral reef ecosystems are not addressed.

Materials and methods

The IUCN Red List of Threatened Species contributes to the conservation of global biodiversity through a system of assessment of the conservation status of individual species (Rodrigues *et al.* 2006; Mace *et al.* 2008). These assessments evaluate the chances of extinction in the foreseeable future based on past and expected trends and identify major threatening factors. In 1994, the IUCN adopted a set of criteria that uses quantitative thresholds for the placement of species into threat categories based on guidelines originally proposed by Mace and Lande (1991). These criteria have been refined and improved through a broad consensus into the current version in use today (Version 3.1, available at http://www.iucnredlist.org, accessed 14 November 2011; for a review of the development of these criteria, see Mace *et al.* 2008). Application of these criteria is a widely accepted method for assessing a species' probability of extinction and its conservation status (e.g. Hoffmann *et al.* 2008). Table 1 briefly summarizes the five major categories of threats considered by the IUCN. All grouper species were assessed by experts for risk of extinction based on these criteria, and data and results of the Red List assessments are freely and publicly available on the IUCN Red List of Threatened Species (http://www.iucnredlist.org, accessed 14 November 2011). Following recent treatments of grouper systematics (Craig and Hastings 2007; Craig *et al.* 2011), a 'grouper' is any member of the genera *Aethaloperca*, *Alphestes*, *Anyperodon*, *Cephalopholis*, *Cromileptes*, *Dermatolepis*, *Epinephelus*, *Gonioplectrus*, *Gracila*, *Hyporthodus* (newly resurrected genus), *Mycteroperca*, *Paranthias*, *Plectropomus*, *Saloptia*, *Triso* and *Variola*. We follow Smith and Craig (2007) and use the family name Epinephelidae (groupers were long-placed in the family Serranidae and are still treated as such in the IUCN database; Craig *et al.* 2011).

Following assessment of all grouper species, we created maps of the distribution of grouper species in each category (Threatened, Near Threatened, Data Deficient, and Least Concern). Distribution shapefiles were created using the software ArcView 3.3 (ESRI, Redlands, CA, USA). A basemap, defined by buffered distances from the shore and bathymetry data, was used as a guide in shapefile creation. Polygons representing the species distribution ranges were drawn and used to clip the basemap. Bathymetry data were based on ETOPO1 (National Geophysics Data Centre) raster data. All shapefiles were merged together into a single shapefile. Using a script in ArcView 3.3, the merged polygons were converted into a raster format with a 10 km by 10 km grid. We examined the assessments for biological/ecological trends, including for body size, depth distribution and susceptibility to fishing. The rasterized maps were then used to calculate the metrics in each grid square under examination (e.g. species diversity, % Threatened species, etc.). We examined the assessments for biological/ecological trends in body size, depth distribution and susceptibility to fishing as they related to Red List status.

Results

Overall, we determined that 20 species (12% of all grouper species) are currently under threat of extinction as defined by IUCN criteria based on past and current trends (Table 2). Of these 20, three were considered 'Critically Endangered', five 'Endangered', and 12 'Vulnerable'. In addition, 22 species (13% of all grouper species) were considered to be 'Near Threatened', meaning that the quanti-

Table 1 Summary of IUCN criteria for listing in a threat category (Vulnerable, Endangered, or Critically Endangered).

Criterion A	Population Reduction: Size of population has been observed, estimated, or inferred to have declined by a considerable proportion (minimum 30%) over the past three generations
Criterion B	Geographic Range: Species has a small range (maximum 20 000 km^2) and is either (i) severely fragmented, (ii) experiencing decline in range area or number of mature individuals, or (iii) is experiencing extreme fluctuations in range area or number of mature individuals
Criterion C	Small Population Size and Decline: Number of mature individuals is small (maximum 10 000) and there is continuing decline (minimum 10%) expected over the next three generations or (i) a continuing decline in the number or per cent of mature individuals in each subpopulation, (ii) extreme fluctuations in the number of mature individuals
Criterion D	Very Small or Restricted Population: Number of mature individuals is <1000 and/or the area of occupancy is <20 km^2 or ≤5 locations
Criterion E	Quantitative Analysis: Quantitative population analysis indicates the probability of extinction in the wild to be ≥10% in the next 100 years

Table 2 List of Threatened grouper species (Vulnerable, Endangered, or Critically Endangered). See Table 1 for description of threat criteria. 'Aggs' indicates species known to form spawning aggregations. 'Threats' are those listed in the IUCN species assessments (http://www.iucnredlist.org).

Species	Common Name	Threat Cat	IUCN Cat	Aggs	Threat(s)	Depth
Epinephelus drummondhayi	Speckled Hind	Critically Endangered	A		Declines, barotrauma undermines management in multispecies fishery, pressures increasing in habitat	Deep
Epinephelus itajara	Atlantic Goliath Grouper[1]	Critically Endangered	A	x	Declines, targeting all sizes, large fish speared, taken in aggregations, recovery may be occurring	Broad
Epinephelus nigritus	Warsaw Grouper	Critically Endangered	A		Declines, barotrauma undermines management in multispecies fishery, pressures increasing in habitat	Deep
Epinephelus akaara	Hong Kong Grouper	Endangered	A		Declines, fishing pressure extensive and intensive all sizes throughout range, multispecies fishery	Shallow
Epinephelus marginatus	Dusky Grouper	Endangered	A	x	Declines, fishing pressure, multispecies fishery, taken in aggregations	Broad
Epinephelus striatus	Nassau Grouper	Endangered	A	x	Declines, fishing pressure extensive in multispecies fishery, taken in aggregations	Broad
Mycteroperca fusca	Island Grouper	Endangered	B	x	Small range, mature fish reduced by fishing	Broad
Mycteroperca jordani	Gulf Grouper	Endangered	A	x	Declines, high and likely increasing pressure, aggregations targeted	Shallow
Epinephelus albomarginatus	White-edged Grouper	Vulnerable	A		Declines, restricted range	Broad
Epinephelus bruneus	Longtooth Grouper	Vulnerable	A		Declines, fished extensively all sizes	Broad
Epinephelus flavolimbatus	Yellowedge Grouper	Vulnerable	A	?	Declines, multispecies fishery	Deep
Epinephelus gabriellae	Multispotted Grouper	Vulnerable	B		Small range, fished extensively and increasingly	Broad
Epinephelus lanceolatus	Giant Grouper	Vulnerable	A		Declines, fishing pressure extensive and species desirable	Broad
Epinephelus niveatus	Snowy Grouper	Vulnerable	A	?	Declines, fishing pressure extensive	Deep
Cromileptes altivelis	Humpback Grouper	Vulnerable	A		Uncommon, current and projected pressure on live fish all sizes, valuable	Shallow
Mycteroperca interstitialis	Yellowmouth Grouper	Vulnerable	A		Uncommon, declines noted	Broad
Mycteroperca olfax	Sailfin Grouper	Vulnerable	D		Small range, reduced size and CPUE from fishing	Broad
Mycteroperca rosacea	Leopard Grouper	Vulnerable	A	x	Narrow range, reduced and pressure continuing, aggregations targeted	Broad
Plectropomus areolatus	Squaretail Coralgrouper	Vulnerable	A	x	Fishing pressure actual and projected, especially for live fish taken from aggregations	Broad
Plectropomus laevis	Blacksaddled Coralgrouper	Vulnerable	A	x	Uncommon, current and projected pressure for live fish, especially juveniles	Broad

[1]The Pacific and Atlantic populations of Goliath grouper have recently been elevated to species status (see Craig *et al.* 2009).

tative thresholds for placement in a threat category were nearly met. Seventy-one species were considered to be of 'Least Concern', and 50 species were considered as 'Data Deficient' for adequate evaluation. Some Data Deficient species could be in a threat category, however, there is currently insufficient information available for a full assessment (see discussion of 'Data Deficient' category below).

Geographic trends

Three geographic areas emerged as having a relatively high absolute number of Threatened species: the Caribbean Sea, coastal Brazil and the Coral Triangle, which consists of marine waters of Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands and Timor-Leste (Veron *et al.* 2009; Fig. 3). Based on the percentage of

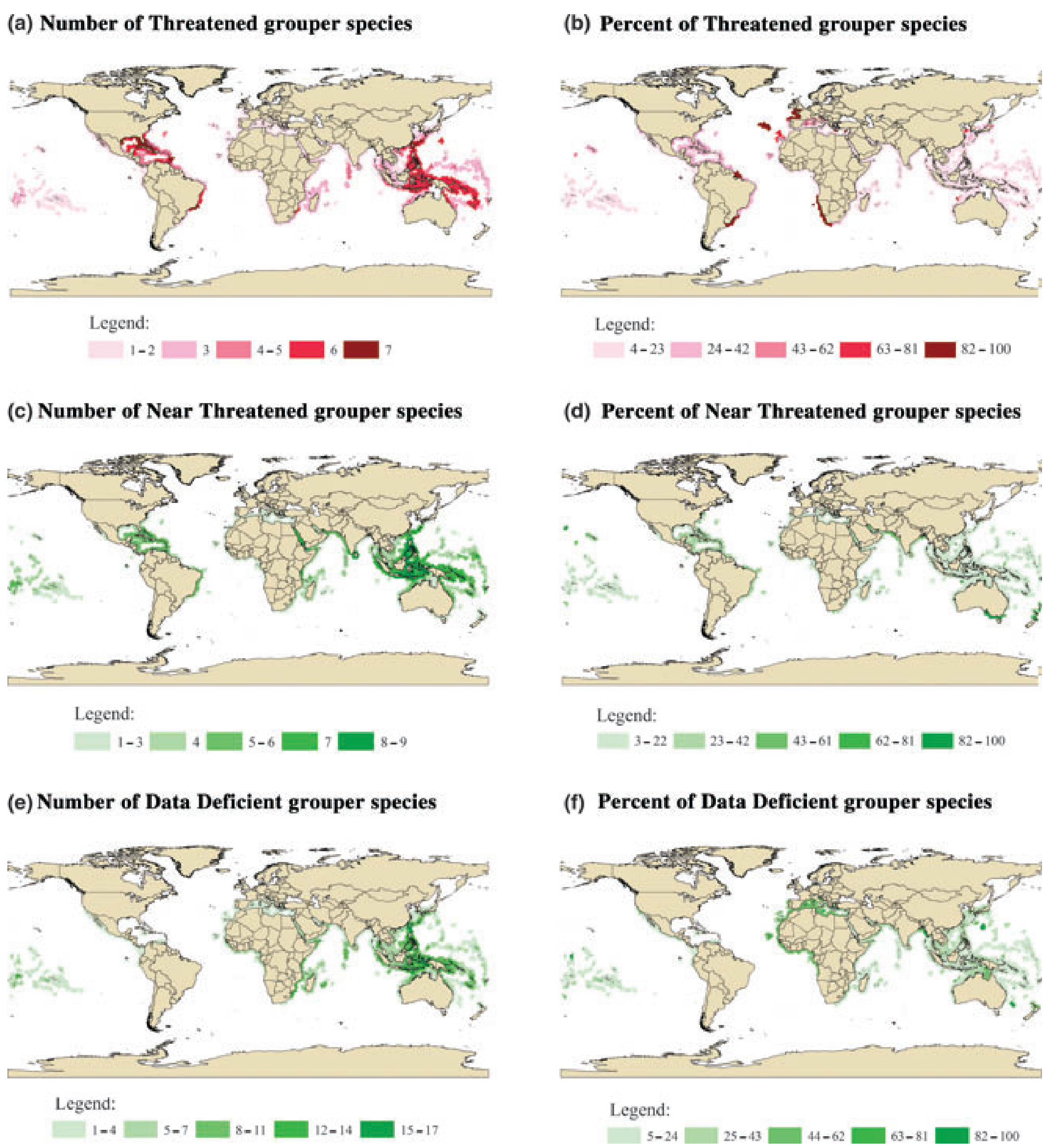

Figure 3 Maps of the distribution of Threatened, Near Threatened and Data Deficient grouper species. (a) Absolute number of Threatened grouper species, (b) Percentage of known grouper species Threatened by location, (c) Absolute number of Near Threatened grouper species, (d) Percentage of known Near Threatened grouper species, (e) Absolute number of Data Deficient grouper species, (f) Percentage of Data Deficient grouper species.

Threatened grouper species known in a particular geographic area, three additional areas of threat were noted: the southwest coast of Africa; the southern coast of Brazil and the Azores islands. Near Threatened species were more common in the Coral Triangle, the Mediterranean Sea, and the Caribbean Sea by absolute numbers, and the Caribbean Sea and south eastern Australia by percentage. Data Deficient species were most common in the Coral Triangle by absolute number and in the eastern Atlantic by percentage.

Size and depth trends

Several patterns were evident when groupers were categorized by their typical depth ranges and maximum reported body sizes (Heemstra and Randall 1993; Craig *et al.* 2011). In general, Threatened and Near Threatened species tended to have larger maximum sizes, whereas smaller species were rarely placed in a threat category (Fig. 4). Data Deficient species occurred in all size categories. In addition, Threatened and Near Threatened groupers were more commonly species whose general depth range is deep (typically >30 m) or 'broad' (common across a wide depth range; Fig. 5). Shallow-water species (typically <30 m depth) had the largest proportion of Least Concern classifications.

Trends in identified threats

Past and projected fishing pressure associated with population declines was considered to be the single major threat, especially when combined with anthropogenic impacts, such as a lack of effective management, and intrinsic aspects of grouper biology. These intrinsic biological factors, such as relatively late onset of reproductive maturity and aggregate spawning, were often noted as contributing to the susceptibility of groupers to fishing. Aggregate spawning is of particular concern given that there are documented examples of fisheries that have targeted these aggregations, directly or indirectly, causing severe population declines (e.g. Sala *et al.* 2001; Sadovy de Mitcheson *et al.* 2008) (Table 2). Other notable risk factors identified for certain endemic species included restricted geographic range and small population size (e.g. island grouper, *Mycteroperca fusca*, sailfin grouper, *M. olfax*, white-edged grouper, *Epinephelus albomarginatus* and multi-spotted grouper, *E. gabriellae*), which could be disproportionally affected by coastal development or a stochastic catastrophic event.

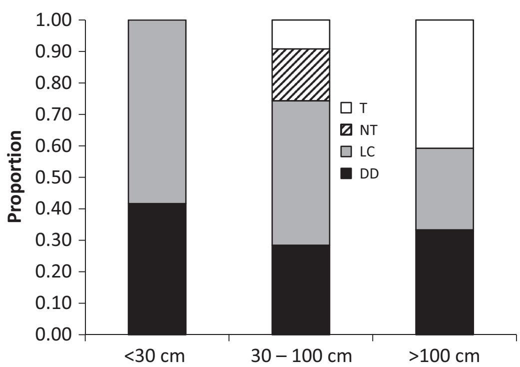

Figure 4 Proportions of groupers in each IUCN category versus their maximum known sizes. Horizontal axis is size groups in cm, and vertical axis is proportions of species in each size group. T, Threatened (Critically Endangered, Endangered and Vulnerable); NT, Near Threatened; LC, Least Concern; DD, Data Deficient.

Discussion

Overall, we recognized 42 species (25% of all grouper species) as facing or nearly facing imminent threat of extinction based on IUCN criteria if threat trends, mainly uncontrolled fishing, continue. Another 50 species (approximately 30%) were considered as Data Deficient for evaluation (see http://www.iucnredlist.org, accessed 14 November 2011, for individual species assessments). While this latter category does not place a species in a threat category, it raises the possibility that more species than currently listed could be threatened and signals the need for additional data collection (see discussion below of 'Data Deficient' category). Our analyses clearly show that many grouper fisheries face serious challenges for long-term

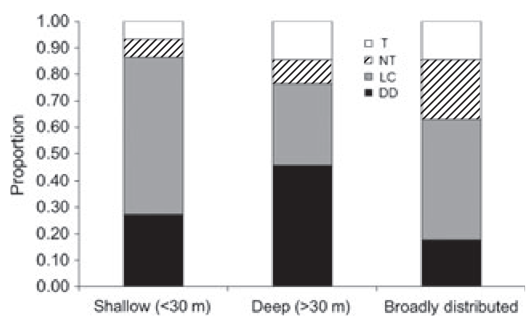

Figure 5 Percentage of groupers in each IUCN category versus known depth distribution. Key as in Fig. 4.

sustainability. At worst, some species or populations will decline to the point of economic, if not ecological or biological, extinction without management action.

FAO grouper landings data

Data on the global landings of several grouper species are documented by the FAO. The FAO database runs from 1950 to the present and currently identifies about 40 groupers to species level, and an unknown number of species are placed under the broadly defined 'Serranidae' (as mentioned above, true groupers, as opposed to seabasses, are now properly placed in Epinephelidae; Smith and Craig 2007) Mycteroperca spp., Groupers nei or *Epinephelus* spp – which account for the highest landings by volume. Not all species documented today have been documented since 1950, and some are no longer reported following fishery declines. Shortfalls in these landings data are most evident for many small-scale, reef-based, multi-species fisheries that are often completely unrecorded (Zeller *et al.* 2005). Also largely unrecorded are the post-settlement to late phase juvenile landings for mariculture grow-out ['fattening' or 'capture-based aquaculture' (CBA)] industry in Southeast Asia (Sadovy de Mitcheson and Liu 2008a). Such data, if they appear at all, would tend to be counted under FAO 'aquaculture' statistics in terms of production following 'grow-out', because 'grow-out' is considered as an aquaculture activity, and not as part of wild capture fisheries. In addition, the common lumping of species into generalized categories of 'groupers' obscures species-specific trends in landings and makes interpretation of these data impossible.

One particularly notable trend in the FAO data is the recent emergence of species-specific categories for groupers that in the past were thought to be too small to be valuable or which were otherwise unmarketable. For example, the species that made up the greatest proportion of the species-specific FAO data over the last decade is chocolate hind, *Cephalopholis boenak*. Reaching a maximum of only 26 cm total length (though more typically rarely larger than 20 cm total length), this species was considered to be of little economic importance approximately 20 years ago (Heemstra and Randall 1993). The relatively recent appearance of smaller species in fishery databases clearly suggests that there is an ever-increasing threat to those previously considered to be of little value to the global market and is a likely result of dwindling stocks of larger and formerly more valuable species. In a similar vein, some important grouper fisheries, especially those targeting larger species, are becoming increasingly dominated by juvenile-sized groupers in landings (e.g. Hong Kong grouper, *Epinephelus akaara*, *longtooth grouper*, *Epinephelus bruneus*, gulf grouper, *Mycteroperca jordani*, and others; Saenz-Arroyo *et al.* 2005; Rhodes and Tupper 2007; To and Sadovy de Mitcheson 2009). The reliance on wild-caught juveniles for CBA places further pressure on some species such as orange-spotted grouper, *E. coioides*, and duskytail Grouper, *E. bleekeri*, among others, even though species like *E. coioides* are also hatchery-produced at commercial levels (Sadovy de Mitcheson and Liu 2008a). Facilitating the documentation of grouper landings over the last two decades has been the availability of species identification guides such as the FAO catalogue of grouper species (Heemstra and Randall 1993). This capability has been further enhanced, particularly in market specimens in which the ability to correctly identify them has been a continual hindrance to the compilation of landings data, with the publication of a field and market guide to groupers (Craig *et al.* 2011).

Implications of geographic trends in threatened species

Groupers are found globally, predominantly in the tropics and subtropics with greatest diversity in the Coral Triangle (CT), where more than 50 species have been recorded. As for many other marine groups, this diversity declines with distance from this area (Bellwood and Wainwright 2002; Bellwood and Meyer 2009). The absolute number of species classified as Threatened is highest in parts of the Caribbean, the southeastern United States, Brazil and Southeast Asia (CT). Putting aside the possible confounding factor that the greatest absolute number of grouper species is present in the CT area, our findings are attributable to one or a combination of factors including (but not limited to) heavy and unmanaged fishing (all areas), and relatively high data availability (e.g. in the Caribbean Sea) which allow for assessments to be conducted. It is also noteworthy that the Western Indian Ocean, a region that remains largely unmanaged, unprotected and heavily fished by artisanal fisheries, does not score highly in any of the categories, including Data Deficient. This is possibly due to the lack of information on groupers and their fisheries in this region. Most species of grouper considered Threatened or Near Threatened have wide geographic ranges (Table 2), thus absolute size of distribution area evidently does not necessarily confer higher resilience to fishing for groupers.

Biological and ecological factors contributing to declines

Of the 20 Threatened species, the predominant criterion used for placement in a threat category was population reduction (Criterion 'A'; Table 1). It was clearly noted in all of these assessments that these declines were because of levels of harvest that appear to be unsustainable. While a simple supply and demand model may explain the rapid depletion of some stocks to levels below sustainable or optimum yield, it should be noted that several aspects of grouper biology and ecology are primary factors in supply side shortages or responses to overfishing.

Perhaps the single most important biological aspect contributing to the decline in groupers is their reproductive biology. Many groupers are long-lived (1–4 decades) and take many years (typically 5–10) to mature sexually making them vulnerable to fishing for relatively long periods prior to entering reproductive function. Many groupers also form spawning aggregations in which fish gather *en masse* at predictable locations and short periods each year for the purpose of spawning (see species accounts in Craig *et al.* 2011) making them highly attractive to fisheries. During the reproductive season, some fisheries temporarily shift their efforts entirely to focus on an aggregating species to benefit from a short-term 'jackpot' fishery (reviewed in Sadovy de Mitcheson and Colin 2012). During aggregations, a large proportion of the adult population from a given area is easily captured over very short periods of time. The development of fishing gear and navigational tools such as portable GPS units has provided fishers with a greater ability to repeatedly locate these aggregations and radically increase their catches. In extreme cases, populations have been reduced to such low numbers that once predictable aggregations no longer form and pressure on them is increasing as more are discovered (Sadovy de Mitcheson *et al.* 2008, http://www.SCRFA.com, accessed 14 November 2011 – global aggregation database).

A few species are particularly at risk because, in addition to fishing pressure, their geographic ranges are small or they are uncommon and highly valued, and therefore sought after with vigour. For example, the island grouper, known with certainty only from the Azores and Madeira (Portugal), Cape Verde and the Canary Islands (Spain), is classified as Endangered. The highfin grouper is naturally rare and attracts high retail value in the Chinese LRFFT and, to a lesser extent, the aquarium trade (Sadovy *et al.* 2003).

Several groupers identified as Threatened share a common habitat preference for deep reefs (i.e. >30 m depth), a surprising finding given the apparent ease of catch and access to shallow-water species that would, in all likelihood, have resulted in sustained fishing pressure for longer periods of time. However, the observation may perhaps indicate that the latter are more resilient to fishing pressure. Shelf edge reefs (40–200 m) support specific assemblages of deep-water snappers and groupers, some of which occur nowhere else (e.g. Olavo *et al.* 2011). These areas should be prioritized for conservation and management because they are not usually considered in marine reserve design (Olavo *et al.* 2011) and are typically targeted by non-selective fishing gear. These factors represent severe challenges to effective management of deep dwelling grouper (see below).

The broader implications of fishing as the major driver of extinction risk

The major threat to groupers, because of their high commercial and food value, comes from overexploitation and lack of effective management. Grouper extinctions have potential implications for ecosystem function and threaten the long-term persistence of fisheries dependent on them for food and income. The demand for live groupers for the international LRFFT, as just one example, already exceeds the estimated annual rate of sustainable grouper production of Indo-Pacific coral reefs (Warren-Rhodes *et al.* 2003) and is probably the principal driver of growth and/or recruitment overfishing in several countries (e.g. Sadovy *et al.* 2003). Grouper farming (mariculture), a lucrative business in itself, does not appear to take the pressure off wild stocks because fishing continues, and may even promote interest in live grouper as a luxury food.

For some species, fishing pressure on previously unexploited life history stages exacerbates the overharvest of their populations and could lead to conflict between fishing sectors that focus on different life history phases. Not only are adults captured and marketed directly for food, but also juveniles are captured for mariculture grow-out (i.e. fattening, ranching, CBA; Sadovy de Mitcheson and Liu 2008a; Tupper and Sheriff 2008). This practice has intensified in Southeast Asia over the last few decades as larger fish become scarce and interest in grouper mariculture to produce highly valued live groupers for food grows; few groupers are regularly produced by hatcheries at commercial levels. Notable examples of grouper species whose primary source is wild-caught juveniles used in mariculture include the Malabar grouper, *Epinephelus malabaricus*, and the Hong Kong Grouper. The giant grouper, *E. lanceolatus*, is nowadays produced extensively by hatcheries but large individuals continue to be taken from the wild for both brood stock and sale at market (loc. cits.). Some groupers identified as Threatened move extensively across reef habitat during their adult life or occupy deep-reef habitat (i.e. below 30 m depth). Marine protected areas (MPAs) have emerged as a promising tool to preserve habitat (Bohnsack *et al.* 2004); however, area-based management is not typically applied to deeper habitat (e.g. Olavo *et al.* 2011). Our completed assessments clearly highlight the need to include outer and deep (>30 m) shelf areas in MPA planning. Moreover, while MPAs in theory offer certain fishery-related benefits beyond MPA boundaries, these are not well or extensively demonstrated at the present time, and most MPAs are small relative to the typical lifetime movements of many larger reef fishes (e.g. Halpern 2003; Sale *et al.* 2005; Little *et al.* 2009). In the case of groupers that aggregate to spawn, this is particularly relevant. Adults of many larger groupers, including a number of Threatened species, undergo extensive seasonal migrations (tens to hundreds of killometre; Bolden 2000; Nemeth *et al.* 2007; Rhodes and Tupper 2008) to and from spawning aggregations. The home ranges of such species are extremely large and greatly exceed the typical spatial dimensions of MPAs (Sale *et al.* 2005; Farmer and Ault 2011). It is only the medium to smaller, less mobile, groupers that are likely to benefit from small MPAs (see below). Currently, it is unclear whether MPAs can actually assist in the recovery of depleted grouper populations without reduction in fishing pressure. Regardless, there is a clear recognition of the need to manage groupers during reproductive periods through spatial or temporal protection of spawning aggregation sites and associated reproductive migratory corridors, combined with other fishery management and marketing controls throughout known spawning times.

In most instances, it is excess and uncontrolled fishing effort, often non-selective for body size or species, that poses the greatest threat to grouper populations, and this is typically not being addressed either by conventional fishery management or by MPA initiatives (Craig *et al.* 2011); additional management measures are needed if grouper populations are to be sustained. Deeper living species would benefit from MPA placement because these are difficult to manage by species-based management. The non-selective capture of deep-water species is often unavoidable and usually fatal because of barotrauma-induced injury.

Beyond the more obvious food and commercial benefits associated with commercial fisheries, we recognize that groupers provide economic and ecosystem benefits. For example, shallow-water recreational catch and release fisheries can be lucrative for supply vendors, while larger groupers are major attractions to divers; the spectacular spawning aggregations of some species were calculated to be far more valuable in diver dollars than as a commercial fishery (Sala *et al.* 2001). The full extent of their ecosystem role is unknown, but as top predators of high combined biomass, it could be considerable.

Reversing the trend: management successes and failures

Given that fishing pressure is the major driver of population declines in most Threatened grouper species, it must be addressed to move towards their recovery. So, what measures have been taken already to manage groupers, how have they fared and what do the outcomes tell us about future actions? A few case studies illustrate the challenges and suggest directions. Grouper management has been attempted in various ways, ranging from minimum size limits to protect juvenile fish, recreational bag limits and commercial fishing quotas, gear and seasonal controls, marine protected areas, to limited entry fisheries and slot sizes.

Some species are protected by a suite of management measures, so it is difficult to determine which one or ones are the most effective, and few such fisheries are adequately monitored to evaluate management outcomes. The coralgroupers (genus *Plectropomus*) in Australia, and Nassau grouper, *Epinephelus striatus*, in Belize Cayman Islands and the

Bahamas are protected by a variety of measures including minimum size, aggregation season/site protection and MPAs. Leopard coralgrouper, *Plectropomus leopardus*, in Australia appears to be well managed and continues as a viable fishery making a valuable contribution to the live reef fish export trade (Samoilys 2012). In stark contrast, the other major supplier of leopard coralgrouper for the international live fish trade is the Philippines where, in Palawan, many of the fish now caught are juveniles and fishers continually have to move to new fishing grounds to maintain catches in the absence of management (John Pontillas pers. comm.). The Endangered Nassau grouper in the tropical western Atlantic continues to decline because of difficulties in implementing the various regulations. Although monitoring of the fisheries is so weak that management outcomes are hard to evaluate, progress is being made, and in our opinion, it is very likely that the populations of this species might now be in considerably worse shape had there been no interventions at all. In Belize, a multi-stakeholder working group has been extremely effective in increasing government and fisher support for its management and has been able to organize some retraining of fishers affected by the management measures (Janet Gibson, pers. comm.). In the Bahamas, NGO support has helped the government and conducted consumer campaigns, through public education and collaborations, to maintain a seasonal moratorium during the reproductive season and to protect several spawning aggregation sites of this species.

Marine protected areas are often considered as a prime conservation measure for sedentary reef fishes. A recent paper documents the success of a marine reserve largely facilitated by community efforts in which biomass of marine fishes increased by over 400% in a 10-year period including groupers of the genus *Mycteroperca* (Aburto-Oropeza *et al.* 2011). There are many reports of the benefits of MPAs to small- to medium-sized sedentary groupers such as *Plectropomus* spp, *Cephalopholis* spp, *Mycpteroperca* spp (e.g. Roberts 1995; Chiappone *et al.* 2000). Studies show that often such species are larger and more abundant in protected areas than in nearby unprotected areas. Broader fishery-wide benefits or population recoveries beyond MPA boundaries except for aggregations however have not been demonstrated for groupers to our knowledge. MPAs are likely to be particularly effective for protecting shelf-edge, drop-off habitats, obviating problems of capture-related barotrauma and non-selective fishing in the case of deep-water species and possibly protecting remaining refuges of shallow-water species. As inshore stocks decline and fisheries search ever deeper areas for resources, there are exciting opportunities to protect such habitats proactively; such action could also encompass deep-water migration pathways and many spawning aggregation sites (Eklund *et al.* 2000; Starr *et al.* 2007; Sadovy de Mitcheson *et al.* 2008). Some species might need regional or international efforts if populations are very large [e.g. Specially Protected Areas and Wildlife (SPAW) Protocol in the Caribbean] or if international trade is a major threat (e.g. CITES, Convention on International Trade in Endangered Species of Wild Fauna and Flora).

The goliath grouper (currently listed as Critically Endangered) shows promising signs of recovery in Florida (USA) following a moratorium on its capture in US waters in 1990 (Koenig *et al.* 2007, 2011). In spite of likely poaching and bycatch, and after only two decades, a species which had dwindled to such low numbers that it was rarely seen is now considered a ‘nuisance’ by local fishermen. In our opinion, this demonstrates that through proper public-private co-management policies and actions, grouper species can recover if fishing effort is effectively controlled. However, concerns remain for this species in that juvenile habitat inshore is not sufficiently protected and this may compromise ongoing population improvement. Moreover, there is no recovery reported elsewhere within the geographic range of this species.

The protection of spawning aggregations through management of the aggregation site, a seasonal fishing ban during the reproductive season, or a combination of the two, has produced positive outcomes in several cases. The red hind, *Epinephelus guttatus*, in the US Virgin Islands was protected at an aggregation site during the reproductive season resulting in significant increases in fish size, fish numbers, catch rates and a recovery in the adult sex ratio (Nemeth 2005). Luckhurst and Trott (2009) reported on increases in red hind size after similar protection following years of declining catches in Bermuda. In the Cayman Islands, multi-year protection of the Nassau grouper during the reproductive season is almost certainly the reason for continuing healthy aggregations, the possible reappearance of a once extirpated aggregation (Whaylen *et al.* 2007) and localized increases in abundance (Philippe Bush, pers. comm. 2009). In Palau, western Pacific, grouper aggregations, particularly of camouflage grouper and squaretail coralgrouper, were fished for local markets as well as for the export LRFFT. For the LRFFT, several sites were rapidly depleted and exports eventually halted. Grouper aggregations are now protected by both national and traditional laws combined with sales bans during the reproductive season, and, although much reduced, aggregations persist (Yvonne Sadovy de Mitcheson and Patrick L. Colin, pers. obs.).

It is clear for groupers, especially larger species, that management can stem declines. While some management exists, challenges remain to ensure enforcement of these measures and to introduce long-term, species-specific, monitoring of grouper fisheries. MPAs need to be very large, or strategically located within a network, to capture the full home range areas of larger species or those with long-distance seasonal reproductive migrations. MPAs need to be well placed and may need to include key nursery habitats. Size limits can help to protect particularly large fecund fish and males in protogynous species, while allowing more juveniles to reach reproductive age. Other measures such as quotas, bag limits and limits to numbers of fishers could be relevant. Regional management, across national boundaries may be needed to address species with broad connectivity.

It is clear that many exploited groupers are conservation-dependent and that successful management will require time, multiple stakeholder involvement, a range of measures, and much improved enforcement. Even with these measures, populations will take many years to recover given the longevity of many groupers. While a better biological and ecological understanding of Threatened and Data Deficient species is clearly needed, a wider public and stakeholder awareness is critical, particularly in regard to biodiversity, ecosystem function and the socio-economic well-being of fishing communities. For the international LRFFT, consumer pressure can be brought to bear by discouraging the consumption of Threatened or poorly managed species. In the case of leopard coralgrouper, for example, the WWF-HK seafood guide distributed in Hong Kong advises against consuming Philippines-sourced fish but recommends Australian-sourced fish (see above).

Interpretation of IUCN criteria

The IUCN criteria for placement of a species in a threat category are based on more than 40 years of extinction risk theory and a wide consensus among many experts (Rodrigues *et al.* 2006). Inasmuch as they have been refined and developed into practical and useful tools, their application to all animal and plant groups is not always a seamless undertaking (Regan *et al.* 2000; Akaçakaya *et al.* 2006). For example, many of the quantitative thresholds for levels of population reduction fit well for terrestrial animals that have relatively low effective population sizes. Many marine organisms, however, have much larger effective population sizes and a greater (potential) dispersal capability provided by the presence of pelagic larval life history stages, which initially led to the belief they could not be threatened with extinction. Nonetheless, the criteria provide a consistent framework for the assessment of extinction risk and, as we learn more about marine fishes, the criteria and categories are increasingly understood to be as suitable and relevant for these as for other types (e.g. terrestrial) of species (Mace *et al.* 2008). Note that the criteria should be considered 'flags of threat' and interpreted as providing 'symptoms of endangerment' rather than denoting actual extinction probabilities (Issac and Mace 1998).

A word of caution on the application of IUCN criteria in the case of exploited species. A demographic analysis of fishing mortality thresholds likely to be associated with high extinction risk showed that the probability of incorrectly assessing species being harvested at F_{msy} was considerable during the initial 'fishing down phase' of a fishery, that is, if the assessment is made during the first three generations since the initiation of the fishery (Type II error). On the other hand, the probability of not identifying species at risk of extinction (Type I error) is substantial if fishing mortality is not reduced (Punt 2000). Because most grouper fisheries have been ongoing for many generations, this suggests that, in general, the risk of extinction in the face of uncontrolled fishing pressure is, if anything, underestimated by IUCN criteria.

Some additional discussion is required for those species placed in the 'Data Deficient' category. This category is reserved for species with too little biological, ecological or distributional information for an assessment to be made using the IUCN criteria, and/or for cases in which a threat has been identified, but where there are insufficient data to apply the IUCN criteria. In some cases, these species may be quite well known in terms of their biology and ecology, often more so than species in a threat category. However, the presence of a distinct threat necessitates discrete data on the effects of that threat. While quantitative data on population trends in abundance or use in fisheries are lacking, an accurate characterization of their threat risk cannot be evaluated. Nonetheless, the category signals the need for additional information to be collected as a priority especially for species likely to be vulnerable (i.e. large size, aggregation-spawner, etc.). Thus, these species may actually be facing a serious risk in terms of extinction, and there is urgent need to compile meaningful data to accurately assess this risk.

Conclusions and future directions

Research actions

For all but the best documented grouper species, we recognize a general lack of basic life history information, reliable fishery-dependent and independent population information, and trade data. While most groupers are relatively well documented among reef fishes in terms of their distribution and habitat type, few are well studied regarding their biology and habitat utilization. Given the recent realization that groupers display differential reproductive modes and behaviour even among closely related species (Sadovy de Mitcheson and Liu 2008b), it is no longer acceptable to generalize and make assumptions about these important biological components, and species-specific studies are needed. Data Deficient species should thus be high priorities for research.

Landings data make up the core of our understanding of population trends. The use of fishery-dependent data as a proxy for overall population size, however, is fraught with hazards and assumptions (Maunder and Punt 2004), especially given that measures of effort are often not available. Fishery-independent baseline data on the abundance of grouper species will be critical to future evaluations of their population stability. This is particularly important in the case of aggregation-fisheries in which 'hyperstability', whereby continued aggregation behaviour can mask declining populations, can be highly misleading in assessing overall abundance (Sadovy and Domeier 2005; Erisman *et al.* 2011). The good news is that most shallow to medium-depth groupers lend themselves well to fishery-independent sampling, such as from underwater visual census surveys (e.g. Samoilys and Carlos 2000; Nemeth *et al.* 2007).

Overall, research trends in fish biology have strayed from answering basic questions about the biology and ecology of many species in favour of investigating more process-oriented hypotheses (e.g. recruitment and dispersal; Sale 2002). Groupers are no exception. However, in the absence of the most basic biological information, we cannot establish biologically meaningful management practices and will not be able to reverse the alarming trends indicated. We also need to better understand the role of groupers in coral reef ecosystems.

Management actions

Despite the importance of groupers in many reef-associated fisheries in the tropics and subtropics, few are managed or monitored. Where data are collected by monitoring the fishery, different grouper species are typically lumped into a single group. This greatly reduces the value of the data because declines in the more vulnerable groupers in multi-species fisheries, which are typically larger, could be masked by compensatory increases in the volume landed of smaller species. This calls for species-specific monitoring. MPAs are widely used as a sole management tool in the tropics yet fishing effort, the major threat for groupers, is rarely managed. Given that the biology of groupers makes them more vulnerable to overfishing than many other reef-associated species, control of effort to within biologically sustainable limits is usually an essential management measure as fishing pressure on grouper populations grows. Groupers that aggregate to spawn certainly require management attention in anything other than small subsistence fisheries. Marine protected areas and/or seasonal protection during the reproductive season can be used to protect spawning aggregations; in some countries, these measures could be effectively used together or combined with sales bans to aid enforcement. MPAs can also be used to protect deep-water habitats and avoid the problem of barotrauma after capture. Given the increasing predominance of juvenile groupers in landings, minimum size management measures may also be advisable.

Beyond scientific information, conservation initiatives require other agents and considerations – for example, political clout/awareness/will, public participation and awareness, etc. (e.g. Sale *et al.* 2008). While management of fishing effort through fishery management and the establishment of MPAs are important steps, community awareness and acceptance, and effective enforcement are paramount for their successful implementation. Numerous studies exist showing the benefits of marine reserves to the ecosystems they protect. However, few adequately show the direct benefits to human communities or fisheries in nearby regions. Moreover, MPAs do not, typically, address fishing effort and hence, unless very big, cannot deal with excessive exploitation on grouper populations. Greater public awareness can lead to support of legislation and action at the consumer end of the supply chain by empowering customers to make better seafood choices, for example, by avoiding Threatened species and selecting certified 'sustainable' species (although see Jacquet and Pauly 2010 regarding concerns over the effectiveness of seafood certification). Major problems still to be resolved whether for fishery management measures or maintaining protection of MPAs are enforcement and illegal fishing. Regional and international actions could possibly be accommodated through the SPAW Protocol or CITES.

Reassessment of species

The IUCN stipulates that red list assessments are valid for only 10 years. However, given the current trends in population declines for many grouper species, 10 years may be too long to wait. Frequent, repeated assessments are necessary to accurately reflect the status of a species based on its risk of extinction. For example, a re-assessment of the goliath grouper recommended a more speedy process because of indications of recovery by increased juvenile numbers in the southeastern United States (Koenig *et al.* 2011). Because assessments focus on adult numbers, it will take time to determine whether the populations of such species increase as a result of protection. This means that assessments must be repeated at various time intervals according to the longevity and growth rate of individual species.

Regional assessments of species

The IUCN provides guidelines for Regional Red-Listing of species (RRL; http://www.iucnredlist.org, accessed 14 November 2011). It is recommended that regional assessments for groupers be undertaken following IUCN criteria. Regional Assessments are often useful because management of resources for migratory species or trans-boundary stocks is best focused at regional levels. The RRL is a useful tool to assess the conservation status of groupers and, when compiled regularly, will be useful for monitoring trends of biodiversity loss or recovery. Additionally, this empowers local initiatives/efforts and forces regional authorities to face the facts and perhaps allows for opportunities to highlight (and reinforce if done regularly) what can be done and what should be done and how.

Concluding remarks

The prognosis for relief from fishing pressure for most grouper species is poor. Whether selective or non-selective, uncontrolled fishing effort poses the major problem for most species, and many are fished intensively and extensively throughout much of their geographic ranges, such that few refuges likely remain for recovery. Many species are among the largest in their multi-species fisheries, yet few are monitored at the species level or managed for sustainable levels of catch, putting them at the more vulnerable end for capture, irrespective of their biology. Even when species can be commercially maricultured (by farming or marine aquaculture based on hatchery-production of young), such as in the cases of Malabar grouper, orange-spotted grouper and giant grouper, there is no indication that such culture production does, or will, take any pressure off wild populations because all three of the above species continue to be taken from the wild. Moreover, there are no management plans to actively substitute wild capture in favour of mariculture production and both activities are likely to continue. MPAs can help to protect sub-populations of certain species, generally the smaller ones, at the local level. However, their typically limited spatial extent cannot address the conservation problems of larger species with wider movements or that migrate long distances and through unprotected areas to and from spawning aggregation sites. The threat from the direct targeting of spawning aggregations is a major problem in many of these larger species and few such aggregations are effectively managed.

Groupers face many of the challenges to their continued existence that are shared among the Earth's vertebrates. Hoffman *et al.* (2010) concluded that one-fifth of all vertebrates are at risk of extinction based on the IUCN criteria. While this stark outlook for the continued health of the world's vertebrates is bleak, hope is by no means lost. Hoffman *et al.* (2010) also demonstrated that without conservation efforts, the rate of loss would have been significantly higher. It is thus critical that we continue to focus on conservation and management efforts for all animal groups even in the face of such dire estimates of extinction risk on a global scale.

Finally, groupers are an important test of our ability to manage and willingness to meet the global fisheries crisis in general. Including as they do some of the most vulnerable species in multi-species reef-associated fisheries, they represent many of the challenges we face in reining in fishing effort generally. While many people might believe that the loss, either through commercial or biological extinction, of the most vulnerable species in multi-species fisheries is an inevitable consequence of meeting increasing demand for seafood, once the groupers have gone the next most vulnerable species are likely to be affected through serial depletions, and so on. The biological and human welfare implications of losing these species, therefore, must be seen to be unacceptable, and ensuring their persistence in viable populations and supplying fisheries a challenge we must not fail to successfully face.

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