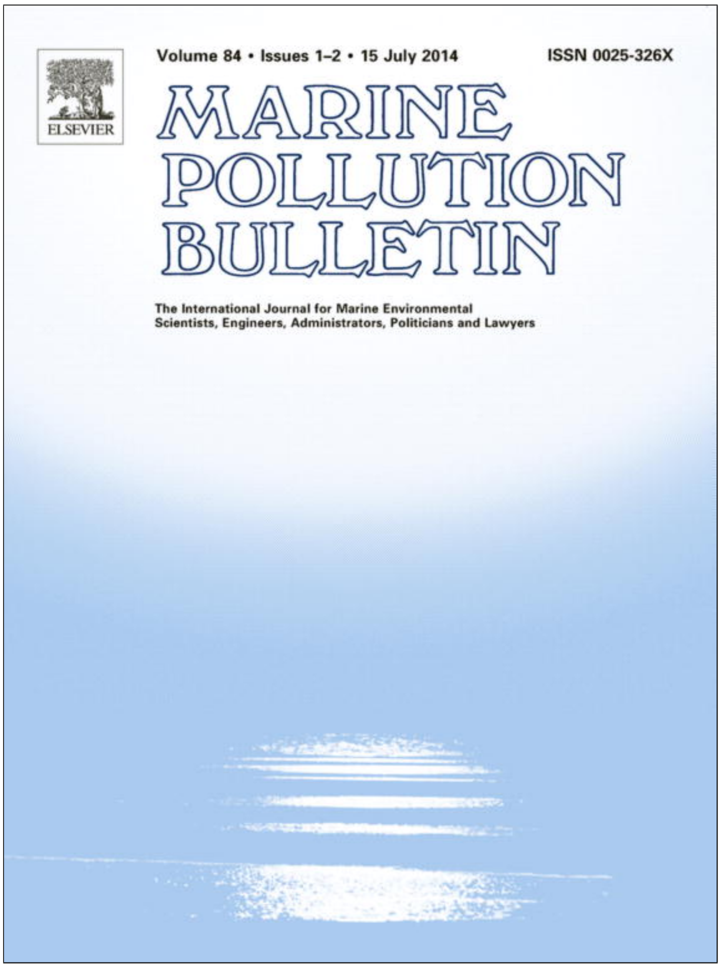
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Viewpoint

Fishing down the largest coral reef fish species

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ABSTRACT

Studies on remote, uninhabited, near-pristine reefs have revealed surprisingly large populations of large reef fish. Locations such as the northwestern Hawaiian Islands, northern Marianas Islands, Line Islands, U.S. remote Pacific Islands, Cocos-Keeling Atoll and Chagos archipelago have much higher reef fish biomass than islands and reefs near people. Much of the high biomass of most remote reef fish communities lies in the largest species, such as sharks, bumphead parrots, giant trevally, and humphead wrasse. Some, such as sharks and giant trevally, are apex predators, but others such as bumphead parrots and humphead wrasse, are not. At many locations, decreases in large reef fish species have been attributed to fishing. Fishing is well known to remove the largest fish first, and a quantitative measure of vulnerability to fishing indicates that large reef fish species are much more vulnerable to fishing than small fish. The removal of large reef fish by fishing parallels the extinction of terrestrial megafauna by early humans. However large reef fish have great value for various ecological roles and for reef tourism.

1. Introduction

About 50 articles have documented the decline of coral reefs around the world and the many causes (Fenner, 2012). Overfishing and destructive fishing are often considered one of the most destructive human activities on coral reef ecosystems (Burke et al., 2011; Brainard et al., 2011). Recently, a flurry of research has found that the effects of overfishing are not spread evenly among coral reef fish, but are concentrated in the largest species. The recent realization that most modern coral reef fish communities are quite unlike natural, undisturbed coral reef fish communities is an example of "Shifting baselines". The idea of shifting baselines is that we notice change in ecosystems over our career, and tend to assume that the way we saw them first was their natural state. But ecosystems have been impacted by humans over a long period of time, and unfortunately new generations accept degraded ecosystems as the standard of natural ecosystems and the goal of restoration attempts (Pauly, 1995; Sheppard, 1995; Jackson, 1997; Jackson et al., 2001; Pinnegar and Engelhard, 2008).

Coral reef ecosystems in the Caribbean in particular were reported by early explorers to have an abundance of megafauna such as sea turtles, monk seals and sharks that are hard to imagine today (Jackson, 1997). Recent studies of very isolated, near-pristine coral reefs have documented abundances of large coral reef fish such as sharks, giant trevally, humphead wrasse, grouper, schools of jacks and bumphead parrots that paint a very different picture of natural coral reefs than most reefs more familiar to coral reef scientists and the general public. In addition, some studies have documented heavy fishing pressure on these species in areas near people and consequent declines, sometimes even resulting in local extinctions.

One of the first papers documenting populations of large coral reef fish on remote, near-pristine coral reefs reported that giant trevallies and sharks were amazingly abundant on the Northwestern Hawaiian Islands (Friedlander and De Martini, 2002). The southeast end of the Hawaiian chain has large islands that have long been populated by humans, and some are now densely populated. The northwestern part of the chain, however, consists of a string of tiny islands that are too small to host anything but temporary small groups of people. The NW Hawaiian Island reefs are virtually swarming with big fish compared to the main Hawaiian Islands. The most common big fish there is giant trevally (*Caranx ignobilis*), a predator which can reach 1.7 m length (5 feet) and 68 kg (150 pounds) maximum. But there are also lots of sharks such as grey reef sharks and Galapagos sharks. These big apex predators compose around half of all the biomass of all the reef fish on these reefs (Fig. 1). In contrast, the main Hawaiian Islands have very few sharks at all. There are about 65 times as many sharks per unit of area in the NW Hawaiian Islands as the main islands. The effect of fishing is very large indeed.

If you snorkel or dive in Hawaii, you will usually be surrounded by small colorful fish (only), which is typical of most coral reefs around the world, although in many places even the small fish

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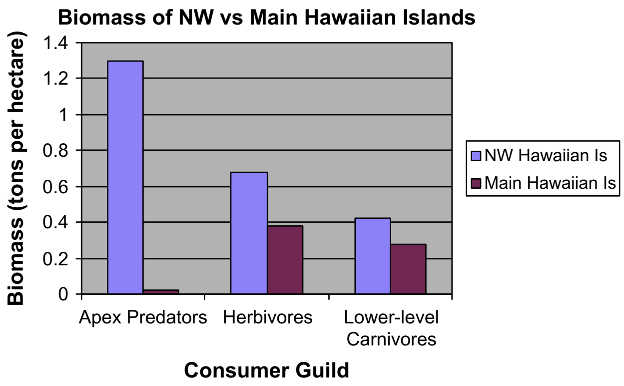

Fig. 1. Reef fish community composition in Hawaii. There are very few humans in the NW Hawaiian Islands, and many in the main Hawaiian Islands. Redrawn from Birkeland and Friedlander (2001).

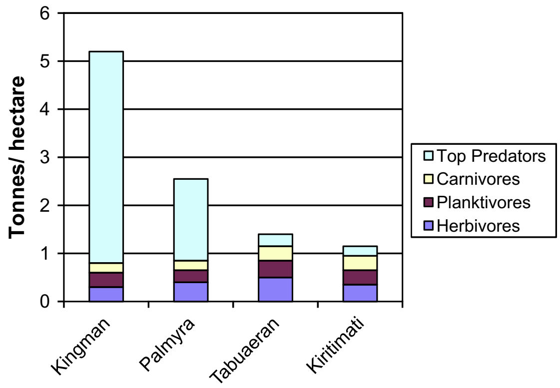

Fig. 3. Reef fish community composition in the northern Line Islands. Human population increases from left to right. Fishing is prohibited at Kingman and Palmyra though Palmyra was historically fished, Tabuaeran has subsistence fishing and Kritimati has subsistence and commercial fishing. Redrawn from Sandin et al. (2008).

are fished down to low abundances. Occasionally in the main Hawaiian Islands, a tiger shark attacks and tragically kills someone, but then people often go out and kill all the sharks they can find, perhaps around 200. Few if any will be tiger sharks. In Hawaii, large numbers of sharks have been killed in 'shark control' programs. "In response to concerns over shark attacks on humans, large scale shark fishing programs were conducted in Hawaii from 1959 to 1976. During this period >4500 sharks were caught within the MHI..." (Papastamatiou et al., 2006). In early 2014, a series of shark attacks in Western Australia has led to 'shark control' programs.

A series of studies have documented what today are astonishing fish biomass on reefs far from people compared to reefs near people, with several studies focusing on the Line Islands, a string of tiny islands south of Hawaii, some of which have no people or no fishing (Stevenson et al., 2006; Pala, 2007; Richie et al., 2008; Sandin et al., 2008). Christmas Island has the most people and most fishing pressure, no fishing is allowed at Palmyra, and Kingman Reef has neither people nor fishing. Total reef fish biomass is highest where there is no fishing, and lowest where fishing pressure is greatest. Note that the differences are by far the largest among the top predators, which are also the largest fish species (Figs. 2 and 3).

Sandin et al. (2008) write: "The earliest historical descriptions of Kiritimati and Tabuaeran document an enormous abundance of sharks and other large fishes that persisted until the early to mid 20th century when declines became apparent. As recently as 1997, fish biomass at Kiritimati was double that observed in our study and was comprised of over 30% top predators, suggesting that large declines in the fish assemblage has occurred within just ten years as the human population rapidly increased due to deliberate relocation. Thus, the low fish biomass at these atolls most likely is due to fishing here, as in many places elsewhere." "Over 50% of the reef fishery is composed of predatory species". "The changes in reef fish assemblage structure are best described as a response to increased fishing pressure from Kingman to Kiritimati... Fishing pressure tends to disproportionately reduce densities of longer-lived, larger-bodied individuals...which are frequently from higher trophic levels".

The Coral Reef Ecosystem Division (CRED) of NOAA, based in Honolulu, surveys coral reefs around all 50 of the U.S. Pacific islands and reefs, and has found similar patterns (Fig. 4). They found huge differences between unpopulated islands to the left in the graph and populated islands to the right. Further, the differences are largest for the apex predators.

The same pattern has been found in the Marianas chain in the northwestern Pacific. Studies by CRED of reef fish in Guam and the Marianas found that fish larger than 50 cm in length were much more abundant around the islands at the northern end of

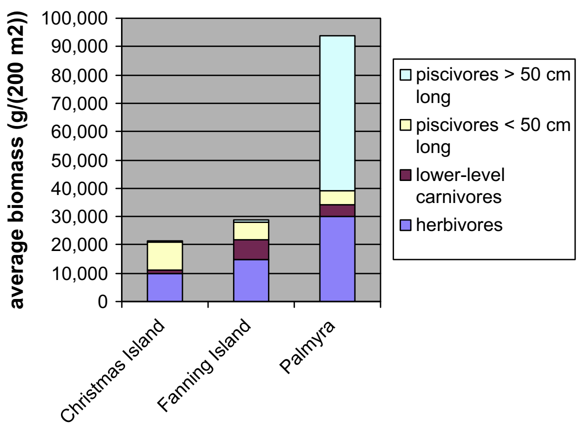

Fig. 2. Composition of reef fish communities on islands in the Line Islands. Fishing is heaviest at Christmas and not allowed at Palmyra. Redrawn from Stevenson et al. (2006).

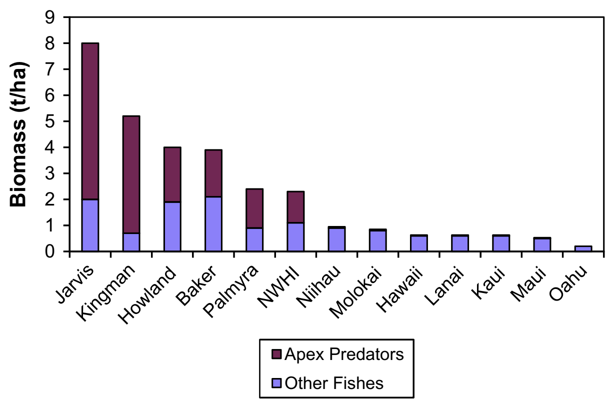

Fig. 4. Fish biomass in Hawaii and the U.S. remote Pacific Islands. The latter are in the Line Islands (Jarvis, Kingman, and Palmyra) and the Phoenix Islands (Howland and Baker), which are all unpopulated. "NWHI" refers to the average for the Northwest Hawaiian Islands, tiny islands to the northwest of the main Hawaiian islands which are the large islands with people. All islands to the right of "NWHI" are populated. Redrawn from Wilkinson (2008), based on data from the Coral Reef Ecosystem Division of NOAA.

the chain (Fig. 5). Human population is concentrated on Guam and other islands at the southern end of the chain, while the middle and northern islands are uninhabited.

In the Indian Ocean, the Chagos archipelago near the center of the ocean has a large reef area, most of which has no people on it and has had little human influence for several decades. The unpopulated atolls have an average fish biomass that is orders of magnitude higher than anywhere else in the Indian Ocean, including MPAs, and as high as the highest level found yet in the Pacific (at Jarvis Island). The one atoll with people in Chagos, Diego Garcia, has lower biomass than the average of the atolls that lack people. The fish community is not heavily dominated by sharks as the reefs in the Pacific are, which may in part be due to a long history of shark poaching by outside fishermen (Graham and McClanahan, 2013; Graham et al., 2013).

Some comparisons between fished and remote reefs may be open to many interpretations due to the many differences between the reefs. For instance, islands and reefs which have high abundances of big fish tend to be very small as well as have few people, while islands that have low abundances of fish not only have higher human populations, they also are much larger, high islands. Large islands have a number of other attributes which may affect fish populations compared to small islands or reefs, such as much more sediment and nutrient runoff. In a very few locations, some of these relationships can be broken, and the results can be very instructive. A good example is Rose Reef, a small reef just south of Guam. It has no island, and thus no people, and is small. As such, one might assume it would have lots of big fish, but it does not (Fig. 5). It is within easy reach of Guam. It is too far away for sediment, nutrients, or chemical pollution to reach from an island the size of Guam from which even sediment plumes do not reach. The low abundance of big fish on Rose Reef can only be explained by fishing.

Williams et al. (2011) document the patterns of reef fish around 39 islands and reefs in the U.S. Pacific, that is, Hawaii, Guam and the Marianas, American Samoa, and the remote U.S. islands. There are many details in the data that cannot be explained by fishing alone. That is to be expected, reef fish populations are affected by a wide variety of factors such as habitat, biogeographic location, and food sources. However, in each of the archipelagos, large fish were more abundant on remote, low population islands and reefs than on populated islands and reefs. Further, the effect shows a gradient with size. The effect is largest with the larger fish, and decreases with decreasing size fish. Small fish are a good control for the many effects of humans other than fishing. Habitat destruction, sediment, nutrients, and chemical pollution should all affect small fish as well as large, and we have no evidence to show they have differential effects on different sizes of fish. Fishing, however, is well documented to have much stronger effects on larger fish than on smaller fish. We know of no other way to explain the results other than by fishing. Further, the effects are present in each of the three archipelagos. Small fish were slightly more abundant on remote reefs than populated reefs, which could be because fish of those sizes are also taken by fishing, or because there are other human impacts that decrease fish abundance in addition to fishing (and thus affect all size fish). It makes sense that both fishing and other factors affect fish populations, but the data in this study show that the lion's share of the effect on large fish is from fishing.

A study in Australia reports that while the Cocos-Keeling Islands in the Indian Ocean (owned by Australia) and which have no fishing, have abundant sharks, sharks are much less abundant on the Great Barrier Reef (GBR) in areas open to fishing (which until recently was most of the reef) (Robbins et al., 2006). In the few tiny areas of the GBR where people are not allowed to go, sharks are abundant as in Cocos-Keeling (Figs. 6 and 7). Surprisingly, in areas where fishing is not allowed but people can go ("no-take" areas), sharks are in low abundance similar to that in areas where fishing is allowed. Apparently, people are poaching sharks in no-take Marine Protected Areas (MPAs), and only no-go areas provide enough protection. The authors were able to measure the rate at which sharks are declining on the GBR, and it is rapid. Fishing in Queensland (where the GBR is) is controlled by the Queensland Department of Primary Industries. They claim they have tightened up regulations (now each fisherman is limited to possession of only one grey reef shark or white tip reef shark) so they say it is well regulated. Each fisherman is limited to possessing one reef shark per day, or a maximum of 365 a year, but anyone can kill all they want and throw them back. Another study (Heupel et al., 2009) used fish catches to measure Catch Per Unit Effort (CPUE) for reef sharks on the GBR. They found higher CPUE indicating more sharks in no-take areas of the park than in areas open to fishing. However, they did not report on no-go areas, or areas that have not had shark fishing. They report that CPUE has not been declining, indicating that populations may not have been declining. Usually, if you can observe and measure something directly like the underwater visual census used by Robbins et al. (2006), that is superior to indirect methods like CPUE, because the more indirect methods require assumptions that often are not, or cannot be, tested.

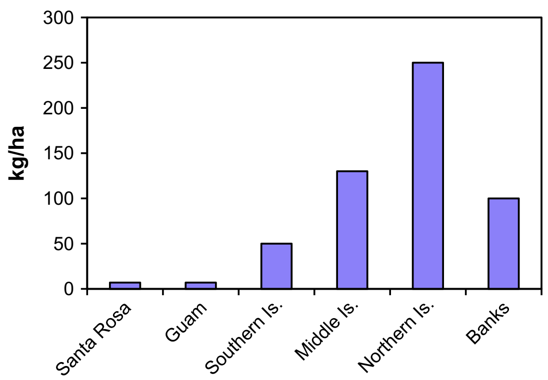

Fig. 5. Large fish biomass in Guam and the Mariana Islands. Santa Rosa is a reef just south of Guam, far enough from Guam not to be influenced by the sediment runoff that is often blamed for the lack of fish around Guam, but close enough to easily be reached by boat. Large fish are defined as fish over 50 cm (20 inches) in length. Human population is concentrated in Guam and the southern islands. Redrawn from Starmer et al. (2008) based on CRED data.

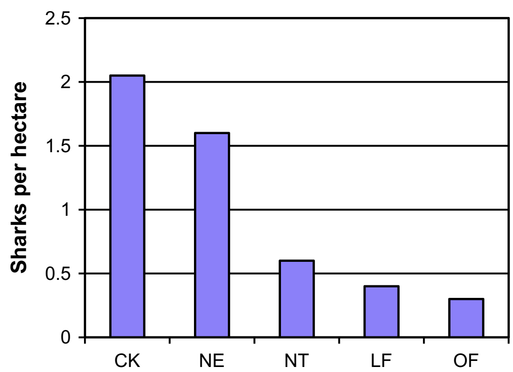

Fig. 6. Whitetip reef shark populations on reefs of the Great Barrier Reef, Australia. CK = Cocos-Keeling Islands of the Indian Ocean, NE = no-entry reefs, NT = no-take reefs, LF = limited fishing reefs, OF = reefs open to fishing. Redrawn from Robbins et al. (2006).

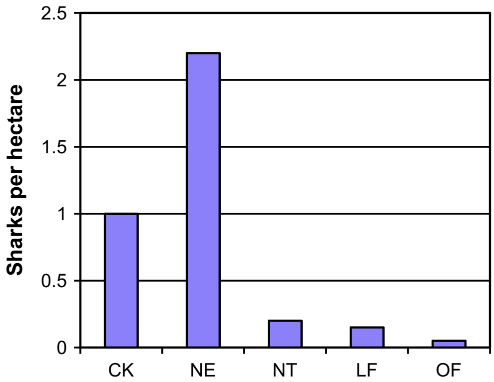

Fig. 7. Grey reef shark populations on reefs of the Great Barrier Reef, Australia. CK = Cocos-Keeling Islands of the Indian Ocean, NE = no-entry reefs, NT = no-take reefs, LF = limited fishing reefs, OF = reefs open to fishing. Redrawn from Robbins et al. (2006).

Robbins et al. (2006) wrote: "Our data suggest that for coral-reef sharks, immediate and substantial reductions in shark fishing will be required for their ongoing collapse to be reversed". "Together, these findings indicate that extirpation of these species from fished coral-reef ecosystems is an immanent likelihood in the absence of substantial changes to coral-reef management". "Inferred and projected declines such as ours appear sufficient to warrant "Critically Endangered" status under the IUCN Red List (A3d) criteria for this study area for both species". "Moreover, the magnitude of the population decline is severe: Median rates of population decline are 7% per annum for whitetip reef sharks and 17% for grey reef sharks. If current population trends continue unabated, the abundance of whitetip reef sharks and grey reef sharks present on legally fished reefs will be reduced to only 5% and 0.1% respectively, of their present-day no-entry abundance levels within 20 years".

The vulnerability of sharks is highlighted in this quote from Nichols (1993): "Sharks possess particular biological characteristics which render them especially susceptible to high fishing pressure, and as such, qualify them as a special case for management. As apex predators, they have few natural enemies. The biological characteristics of sharks – long lived, slow growth rates, low fecundity and reproductive rates (some species do not reproduce every year), long gestation period, relatively large size at first spawning, and strongly density dependent recruitment – result in shark fisheries being particularly sensitive to over-fishing". Hilborn (2005) wrote: "Species that have few offspring (e.g., sharks and rays) or live a long time will intrinsically have a lower rate of increase". "Long-lived and low-fecundity species are particularly prone to depletion because the exploitation rate that is sustainable is much lower".

Similar findings have been reported from the Caribbean. Ward-Paige et al. (2010) used the massive database from trained REEF volunteer divers, using reports from over 76,000 underwater surveys, which is just the kind of survey data set needed to assess rare species. Significant numbers of sharks were found only in areas of very low human populations, or in very well protected areas. Nurse sharks were exceptional, being found near humans as well as farther away. Nurse sharks have low fishery value. Historical records report that sharks were plentiful in the past, as recently as the 1950s in some areas. Shark catches increased dramatically in recent decades in many places. For instance, landings of sharks in the Gulf of Mexico tripled between 1980 and 1989, and Caribbean elasmobranch landings peaked at more than 9 million tons in 1990 (Ward-Paige et al., 2010 and references therein). The authors used a model to calculate the effect of different levels of fishing pressures on different shark species, and found that under density dependent conditions all species declined to 1–14% of their initial abundance within 50 years when 10% of the population is removed per year. Under density-independent conditions all but one species declined with 10% removal. The authors state that "Sharks on reefs can be particularly vulnerable to the growth and spatial expansion of human populations. As a group, sharks are susceptible to even mild levels of fishing mortality given their late age of maturity, slow growth, and slow reproductive rate". The facts that high populations of sharks are present only where there are very few if any humans, but can also be abundant where they are vigorously protected from fishing, indicates that, consistent with the model results, small amounts of fishing deplete these fish.

Nadon et al. (2012) recorded populations of reef sharks on 46 reefs in the U.S. Pacific areas, including both populated and unpopulated areas. They recorded sharks using a towboard (manta board) technique that records much lower levels of sharks than transects, because divers attract sharks, particularly in areas where divers are rare or novel. The rapid motion of the towboard means that divers recording sharks in front of them record fewer sharks that they attract, most of which follow them from behind. They found that in areas of few people and low nutrients, shark populations increased with increasing temperature, though there was considerable scatter in the points. They also found that in areas of few people and high temperature, shark populations increased with increasing nutrients, though the effect depended on just three points. But the most dramatic effect was the effect of humans. It took as little as 200 people within 200 miles of a reef to produce low shark populations. Only when there were less than 200 people within 200 miles were there greater amounts of sharks (Fig. 8). Only fishing can have an effect over 100 miles: sediment, nutrients, and pollutants do not reach more than about a mile from a relatively small island such as those in the U.S. Pacific.

Nadon et al. (2012) found that shark populations in inhabited areas are generally at least an order of magnitude less than in uninhabited areas. The differences are most dramatic for grey reef sharks, with the differences between the site where they are most abundant (Jarvis Island) about three orders of magnitude higher than in the areas with human populations, and the difference between the median uninhabited location and the inhabited locations being about two orders of magnitude. Grey reef sharks were by far the most common species in areas without people. American Samoa had about 4–8% of the number of all reef sharks expected if there were no people, Hawaii about 3–7%, and the Marianas 4–10%. For comparison, Maximum Sustainable Yield (MSY) is at about 33–50% of virgin biomass. So these shark populations are heavily overfished.

Humphead wrasse, also called Napoleon or Maori wrasse (*Cheilinus undulatus*) are similarly threatened. These fish grow to 2.3 m long and 191 kg so are more massive than most reef sharks. They are found in the Indo-Pacific, and feed mainly on shelled invertebrates. They are taken in the live food fish trade from an expanding area that covers much of the western Pacific, and sold in Hong Kong and Taiwan, where they fetch amazingly high prices. Because huge numbers are taken in the life food fish trade (the trade is worth around US$1 billion per year), they have been put on the CITES list. CITES enforcement is by the importing country. Taiwan and Hong Kong are the importing countries, and have a strong conflict of interest since their people are the ones that value eating these fish so highly. But they are also taken by local fishers wherever there are people. In Guam, they sell for $11 a pound (circa 0.5 kg) so a 100 pound fish can fetch $1100, and so are irresistible. Their abundance is inversely correlated with the abundance of people – where the human population is greatest they are nearly absent, but where there are no people or fishing is not allowed, they are most abundant (Fig. 9). The remote and uninhabited

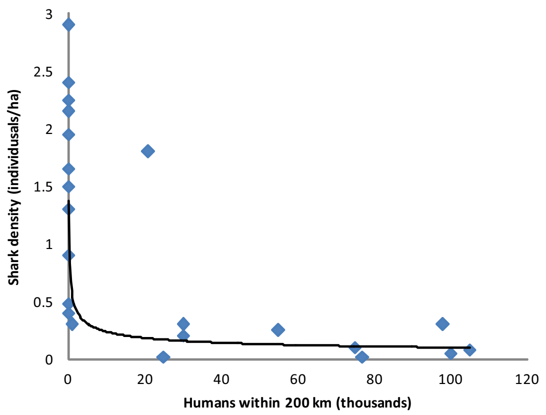

Fig. 8. The densities of sharks on reefs in the U.S. Pacific in warm water where nutrients were low. High densities are only found when there are less than 200 people within 200 miles of the reef (with one exception). The effect is a very strong one, with most dots close to the line. Redrawn from Nadon et al. (2012), fitted with a power function.

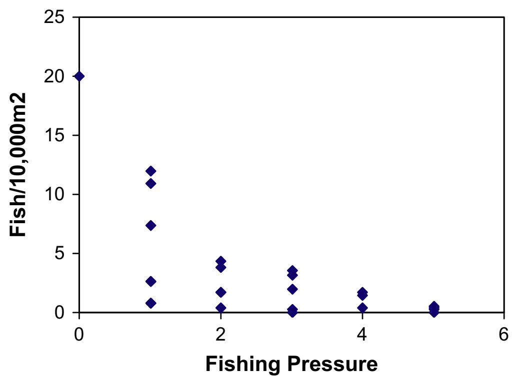

Fig. 9. Abundance of humphead wrasse as a function fishing pressure, which was assessed partly by human population density, but also local fishing practices. Redrawn from Sadovy et al. (2003).

Phoenix Islands and Wake Island (a U.S. military base) have some of the most abundant populations known (Sadovy et al., 2003). The populations of this species are declining, and an expert review panel applying standard criteria for assessing the danger of extinction used by the International Union for the Conservation of Nature (IUCN) Red List of Endangered Species, designated this species as "Endangered".

Sadovy et al. (2003) writes: "This species is particularly sensitive to fishing pressure. In most fished areas, density and body size have dropped substantially. It appears to be particularly heavily targeted and depleted in SE Asia and in some places faces extirpation". "Other giant reef fish share many problems..." "...humphead wrasse in recent years fetching as much as US$130/kg at retail". "Probable extirpations at edge of range sites signal the start of range reduction, an early step towards extinction". "The prognosis for the persistence of exploited populations of *C. undulatus*, under current conditions and given the biology of the species is poor. Conservation and management are needed to ensure it persists in viable numbers wherever exploited". "The humphead wrasse is particularly vulnerable to exploitation at anything other than the lowest levels of fishing pressure".

Bumphead parrotfish (*Bolbometopon muricatum*) are another large Indo-Pacific reef fish. They grow to 1.3 m (4 feet) long and 46 kg (101 pounds), eat coral and algae, and commonly travel in schools of 30–50 (Bellwood et al., 2003), though rarely schools can reach as many as 500 (A. Friedlander, personal comm.) or even 700 fish (S. McKenna, personal comm.). They are abundant in some areas, such as Wake and the northern lagoon of New Caledonia. They were abundant enough to dominate the fish catch on islands in Fiji when night spearfishing was introduced (Dulvy and Polunin, 2004a) and dominate the catch currently in areas of the Solomon Is. (Aswani and Hamilton, 2004). Because of the large individual size and size of schools of these fish, schools can be a large component of the fish biomass on a reef. On the Great Barrier Reef, they are most common near the reef crest at the northern end of the reef, though they also extend to the southern end of the reef. At night they sleep in the same schools, either in the open or in holes and tend to sleep in the same area each night. As a result, they are particularly easy to spear at night until the entire school has been extirpated. Populations once again are inversely related to human populations (Fig. 10) (Bellwood et al., 2003; Bellwood and Choat, 2011). C. Birkeland and G. Davis report (personal comm.) that big schools of bumphead parrots were common in Guam in the 1960s, but they were spearfished out in the 1970s, and now are rare. Hensley and Sherwood (1993) confirm that they are now rare in Guam; Dulvy and Polunin (2004a) suggest they might be extinct on Guam, though G. Davis reports having seen some new recruits in recent years. In spite of this, night spearfishing on SCUBA remains legal in Guam, and it is perfectly legal to spear as many bumphead parrots as you can find, if you can find any. In Fiji, interviews with people revealed that when night time SCUBA spearfishing came to an island, the markets were filled with bumphead parrots, they were half or more of all fish in the markets. Now, in those same areas, they are rare and not seen in the markets. On some islands in Fiji they have been driven locally extinct by fishing (Dulvy and Polunin, 2004a). Fenner (unpublished) conducted key informant interviews with fishermen in American Samoa, asking if they had seen bumphead parrotfish in the past. Four reported having seen schools in the past, from 4–6 to 30–50 individuals. Each school was in a different location, kilometers apart. The largest school was reported by a fisherman who found where the school slept. He speared them at night and returned repeatedly until he could find no more. Since then, less than one individual per year has been sighted over the last 10 years. They are close to local extinction primarily because of fishing. In the Solomon Islands, in some areas they currently dominate markets, and in areas near people, populations have decreased and fishers go farther to find them (Aswani and Hamilton, 2004). Choat reports (personal comm.) that a small group of spearfishers can fill a large

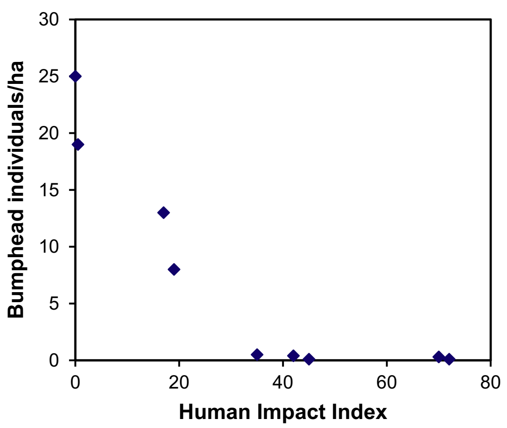

Fig. 10. The abundance of bumphead parrotfish as a function of human population density, redrawn from Bellwood et al. (2003). Note the similarity to Figs. 9 and 10. In spite of the fact that bumphead parrotfish and sharks are among the most distantly related fish on reefs and in very different functional groups, they are affected by fishing in the same way, because of their large size.

skiff with them in a single night, while in the Solomons it is reported that a single fishing party can catch over 500 kg of them in one night (Aswani and Hamilton, 2004). Bumpheads spawn in groups, so it is possible that spawning is stimulated by the presence of a group (Hamilton et al., 2008), so it may be that once populations are low enough they have trouble spawning, so small populations could completely fail even if controls were later enforced (Bellwood and Choat, 2011). Their ability to replenish their populations appears to be unusually limited.

Findings are consistent:

- "Preliminary studies have identified *B. muricatum* as a group spawning species, a behavioural trait that is frequently associated with over-exploitation". "The large size, schooling behaviour and nocturnal aggregation of *B. muricatum* make it a lucrative and highly prized target of many subsistence and artisanal nighttime spear fisheries in the Pacific". Hamilton et al. (2008).
- "Schooling is another life history trait that impedes sustainability. Species that school are highly vulnerable to fishing gear, and there is often little feedback to harvesters or managers of declining abundance through the catch rate, because the fishing fleets are able to maintain good catches on the schools even though abundance might have rapidly declined." Hilborn (2005).
- "Populations that form dense spawning or mating aggregations are particularly susceptible to loss of populations, even by artisinal fishers". Myers and Ottensmeyer (2005).
- "This large conspicuous reef fish was formerly a prominent and abundant member of reef fish assemblages and catches, but is now encountered infrequently throughout large parts of its range". "...this species may be extinct at the Marshall Islands and possibly Guam..." Dulvy and Polunin (2004).
- "*B. muricatum*, in particular, is highly susceptible to spearfishing activity..." Bellwood et al. (2003).

Giant groupers (*Epinephelus lanceolatus*) in the Pacific (also called Queensland groupers in Australia) can grow to well over 2.7 m (8 feet) long and 300 kg (660 pounds). They appear to be rare everywhere, including reefs without people. However, a similar species in the Caribbean, the goliath grouper (*Epinephelus itajara*), which grows to at least 2.4 m (7 feet) and 310 kg (682 pounds, and possibly 455 kg or 1001 pounds!), is a different story. Although they are now rare in the Caribbean, in Florida there are pictures of the trophy catches from tourist fishing boats called "headboats" that painted a different picture in the past. Old photos show lots of huge goliath grouper, sometimes a whole row of them, from a single day's fishing by one tour boat. Today, the photo of the trophy board almost always has mostly smaller fish (McClenachan, 2009a,b). Goliaths have been protected in U.S. waters including the Florida Keys since 1990. Now if you dive there, you have a good chance of seeing a juvenile, maybe 3 feet and 100 pounds. Under protection, their numbers are increasing rapidly, though it will be some time until the giant sizes are reached. Meantime, some recreational fishing operators have discovered that there are fishers who find it extremely exciting to hook a huge fish, even if the hook is barbless and the fish is released. So there are tour companies that specialize in catch and release fishing for goliath grouper (see: http://www.floridalighttacklecharters.com/gallery_extremefishing.htm).

Goliath groupers form spawning aggregations which could provide renewable economic benefits from dive tourism. In Belize, dive tourism at spawning aggregations of groupers and snappers can produce 20 times the income from fishing the aggregations (Heyman et al., 2010). Goliath groupers also have the potential to provide biocontrol for the rapidly expanding populations of lionfish (*Pterois volitans* and *Pterois miles*) in Florida and the Caribbean. Goliaths eat venomous fish and the ability of large groupers to control lionfish is suggested by a finding that lionfish are seven times more abundant outside Marine Protected Areas than inside (Mumby et al., 2011).

Fishing has long been known to usually remove the large fish first (e.g., Ricker, 1946; Jennings and Kaiser, 1998; Jennings et al., 1999; Pitcher, 2001; Heino and Godo, 2002; Dulvy and Polunin, 2004b). The incentive is for a fisher to go for the big ones. In American Samoa, a fisherman who speared a large terminal male humphead wrasse sold it for $120 (and got his name and picture in the newspaper). If he had speared the most common fish, a surgeonfish, it would have brought about $1–2. So the big fish was 60–120 times more profitable per fish (Fenner, unpublished). Fishermen respond to these sorts of incentives just like anybody else. It is usually more profitable to take the big fish (though there are specific fisheries for small fish, such as anchovies, herrings, and sardines where large numbers can be found, but not on coral reefs).

2. Fishing down the food web

It is even possible to get a measure of fishing pressure by recording the sizes of fish present, (Graham et al., 2005). Over decades, fishing can begin with the largest fish, then once they are depleted move to the next size fish, and so on down to the smallest that are still profitable. This is called "Fishing down the food web" (Pauly et al., 1998; Pauly and Palomares, 2005). Think of the size range for reef fish – if reefs in an area have 1000 species of fish, how many are large enough that people fish them, and how many are so small no one would fish them? The most diverse families of fish on reefs are gobies, blennies and damselfish, and they are too small to be fished by any but the most desperately poor fishers. So at the small end of the size range on reefs, there are huge numbers of species that are too small to be fished. At the large end of the size range, there are just a few species, which are highly prized catches. Fishing pressure increases with the size of the fish. In addition, the numbers of individuals in a species decreases with the increasing size of the species. There are huge numbers of damselfish on most reefs, but even on unfished pristine reefs where half of the biomass is large fish, there are many fewer sharks, bumphead parrots, humphead wrasse and giant grouper than damselfish. Even at Kingman Reef, where apex predators are 85% of the biomass, they represent a minute portion of the total number of reef fish individuals, which are dominated in number by tiny planktivores (Sandin et al., 2008). The most abundant fish species on reefs where it occurs is a surgeonfish (*Ctenochaetus striatus*) that reaches just 26 cm length. All this is because the larger the size of the individual, the more it takes to feed them (Colinvaux, 1978). A reef can feed vast numbers of damsels, but only a limited number of sharks, humpheads, bumpheads and giant grouper. So big fish are less abundant than small fish, and more heavily fished. The result is that they are much more rapidly depleted.

There is now a quantitative measure of vulnerability of fishing, which incorporates a variety of things about fish that make them vulnerable to fishing (Cheung et al., 2007). For each species of fish, FishBase (www.fishbase.org) now gives the "vulnerability index", which is the quantitative measure of vulnerability to fishing (Cheung et al., 2007). The index has a range from 0 for no vulnerability to 100 for maximum. Each of the different kinds of the largest reef fish, like sharks, humphead wrasse, bumphead parrots, and goliath grouper, all have vulnerabilities on the order of about 75. Small fish have much lower vulnerabilities, often on the order of 25–35. The striped bristletooth (surgeon), *C. striatus*, which is one of the most abundant reef fish most places where it is found in the Indo-Pacific (Lieske and Myers, 2001), has a vulnerability less than 14. The largest species of reef fish are highly sensitive to fishing, but the small fish are much more resistant to fishing, with the most abundant species being highly resistant.

On land, humans have been implicated in the extinction of large mammals and birds, which often disappeared about the time humans arrived on a continent (McGlone, 2012; Rule et al., 2012; Morell, 2014; Allentoft et al., 2014) such as North America or New Zealand. While the megafauna disappeared, the smaller species survived. Mice and rats do particularly well. Other hypotheses have been proposed for the cause of the loss of terrestrial megafauna about the time that humans arrived at an area or acquired advanced hunting technology, such as climate change, but although some studies find that climate change was part of the cause or the primary cause (Balter, 2014; Boulanger and Lyman, 2014), most find that humans were either part of the cause or the most likely cause (Perkins, 2011; Lornezen et al., 2011; Kerr, 2012; Prescott et al., 2012).

3. Values, alive or dead?

Tourism associated with the Great Barrier Reef is worth roughly $2 billion a year, and provides far more income to Australia than the fisheries on that same reef. Tuna fishing over the entire Pacific is worth about $1.6 billion dollars a year. Reef tourism in the Caribbean is about $6 billion a year, and it is similarly large in the Florida Keys. Reef tourism is a far larger industry than reef fishing and even larger than tuna fishing.

"About half a million divers find, photograph and swim with sharks every year, contributing millions of dollars to local economies" (Topelko and Dearden, 2005). Economic benefits can be up to 30% of the annual GDP of a small island country (Gallagher and Hammerschlag, 2011). Palau has a shark diving industry which contributes $18 million per year to the Palau economy and which is 8% of the gross domestic product of Palau. The annual tax revenue to the government is $1.5 million, or 14% of all business tax revenue. A single shark is calculated to be worth US$1.9 million dollars during its lifetime to the dive tourism industry in Palau, compared to just US$10,000 for the total fisheries value of all sharks. The tax revenue from shark diving is about 24 times as large as for the entire fishing industry there (Vianna et al., 2010).

4. Encouraging future signs

Australia protects humphead wrasse, as does Niue. Palau has now protected all its sharks, plus its humphead wrasse and bumphead parrots. Hawaii and the Northern Marianas Islands have now protected all their sharks. In 2012, American Samoa protected all its sharks, Humphead Wrasse, Bumphead Parrotfish, and Giant Grouper. It remains to be seen whether others will follow suit and whether there is much chance that recovery of spectacular or of useful populations of large fish can be achieved.

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