Benefits beyond boundaries: fishery effects of marine reserves

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Teaser: The use of marine reserves in fisheries management is controversial but evidence is growing fast that they protect species and their habitats, augment catches beyond their boundaries and promote fishery sustainability.

Marine reserves are areas of the sea where fishing is not allowed. They provide refuges where populations of exploited species can recover and habitats modified by fishing can regenerate. In some places, closed areas have been used for fisheries management for centuries, and until recently natural refugia also existed, inaccessible through depth, distance or adverse conditions. Developments in technology have left few areas beyond the reach of fishing. Recently, the idea of marine reserves as fisheries management tools has re-emerged, developing from ecosystem management approaches, and observations of incidental fisheries benefits from reserves established for conservation.

Marine reserves are predicted to benefit adjacent fisheries through two mechanisms: spillover of adults and juveniles across borders, and export of pelagic eggs and larvae. Inside reserves, unexploited populations increase in size and individuals live longer, grow larger and develop increased reproductive potential [1]. Enhanced production of eggs and larvae inside reserves is predicted to lead to export and increased settlement of juvenile animals outside the boundaries.

Using marine reserves for fisheries management is controversial. Critics argue that most commercial species are too mobile to benefit, that marine reserves are only appropriate in very specific cases (usually small scale tropical fisheries) and that it is too risky to implement marine reserves as fisheries management tools on a larger scale until we have more experimental proof of their efficacy. Until recently, most insight into the function of marine reserves came from theoretical studies. However, empirical evidence for the effects of marine reserves on protected populations is growing and demonstrations of effects outside their boundaries are now emerging from a wide range of habitats and fisheries. Here we review this new body of evidence, focussing on reserves that have been effectively enforced for at least five years, and drawing upon studies of more limited fisheries closures that provide insight into how fully protected reserves can work (Gell and Roberts [2] provide a more detailed analysis and 16 case studies).

Magnitude of build-up of spawning stocks in marine reserves

There is now compelling evidence from a wide range of ecosystems around the world for large, rapid and sustained build-up of biomass of commercially important species within marine reserves. In the Tsitsikamma National Park in South Africa (established in 1964, making it one of the oldest reserves in the world) densities of a commercially important sparid fish, *Chrysoblephus laticeps,* were an estimated 42 times higher than in nearby fishing grounds [3]. A more recent study there found that experimental catch per unit effort (CPUE) for four shorefish species were 5-21 times greater than in exploited areas [4].

In the Scandola Nature Reserve in Corsica, densities of 11 fish species were five times higher in no-take than in fished sites after 13 years of protection [5]. Experimental CPUE for lobsters inside the Columbretes Island Marine Reserve in Spain were between 6 and 58 times greater than from fished sites [6]. Also in Spain, pen shells are now 12 times more abundant in the 100ha no-take zone of the Tabarca Marine Reserve (est. 1986) than in nearby fished areas [7]. Russ and Alcala [8] reported a 7-fold increase of larger predatory reef fish after coral reefs were protected for 11 years at Apo Island in the Philippines.

Dramatic increases in body size have also been reported. In three temperate rocky reef reserves of New Zealand, protected between 5 and 20 years, abundance of snapper (*Pagrus auratus*) larger than the minimum legal size was 14 times greater than in fished areas [9]. After five years of protection, 35% of blue cod (*Parapercis colias*) inside New Zealand's Long Island-Kokomohua reserve were over 33cm long, compared to less than 1% in nearby fished areas [10]. In the Maria Island Reserve in Tasmania, large fish became more than three times more common after 6 years of protection [11]. In the Everglades National Park in Florida, USA, (est. 1985) the modal size of grey snapper (*Lutjanus griseus*) was 25-30cm compared to 15-20cm in exploited areas, and 66.2% of fish in the protected area were above the legal capture size, compared to 15.6% and 29.6% at two exploited sites [12].

Increases in animal abundance and size in marine reserves translate into increased reproductive potential. In New Zealand reserves, egg production of lobster (*Jasus edwardsii*) at deep water sites increased by 9.1% per year of protection [13], and snapper egg production was 18 times higher than in fished areas [9]. After over 20 years of protection in the Edmunds Underwater Park in Washington State, USA, lingcod (*Ophiodon elongatus*) produced 20 times more eggs than in adjacent fished areas and copper rockfish (*Sebastes caurinus*) 100 times more [14]. Rodwell *et al*. [15] estimated that 70% of the biomass of fish in Kenya's Mombasa Marine National Park was reproductively active compared to just 20% in nearby fishing grounds.

Increases in protected populations are often rapid, frequently doubling or tripling in 2-5 years (Boxes 1 and 2). Stocks of five families of exploited reef fish tripled in biomass inside reserves within five years of protection in St Lucia [16]. Experimental fishing CPUE in the De Hoop Marine Reserve in South Africa was an order of magnitude higher than from sites outside after 7 years of protection [17]. In the Florida Keys, densities of yellowtail snapper (*Ocyurus chrysurus*) increased by more than 15 times in the fully protected Sanctuary Preservation Areas in 4 years [18]. It is also evident that increases can be sustained well beyond the first few years of protection. Russ and Alcala [8] reported a continuous linear increase in densities of large predatory fish in the Apo Island Reserve, Philippines, over 11-years of protection. Kelly *et al*'s [13] findings of sustained rates spiny lobster increase in New Zealand included data from reserves up to 21 years old. In Merritt Island National Wildlife Refuge in Florida, reserve effects have built up over decades as long-lived fish have grown (Box 3).

Which species and habitats benefit from reserve protection?

Species that respond most rapidly to protection are often relatively sedentary and spend much of their life in reserves. Good examples include invertebrates such as scallops on Georges Bank [19] (Box 1) and bivalves in Fiji [20] (Box 2). Many coral reef fish are relatively sedentary and have benefited rapidly from protection [8,16,21]. In temperate waters, less mobile fish such as flounder have responded strongly to fishery closures [19] (Box 1).

Evidence is also increasing for the role of marine reserves in protecting more mobile animals. For example, many species of lobsters have seasonal movements on scales that might be expected to preclude them from protection in small reserves. However, there is now convincing evidence from the Mediterranean [22], New Zealand [13], Australia [11], Bahamas [23] and Canada [24] that lobster stocks do build up in reserves and that for some species a proportion of the population show high levels of site fidelity [24,25].

Fish capable of moving long distances were not expected to benefit from protection, but tagging studies revealing intra-species differences in movement behaviour are forcing us to rethink our expectations of reserve performance, and helping to explain unexpected beneficiaries from reserves seen in field studies [26]. Just like lobsters, in many fish species a proportion of the population may remain within a relatively small area, whilst others undertake significant movements. The resident fraction allows the build up of biomass and reproductive capacity within a reserve. The more mobile element of the population ensures that benefits are exported beyond boundaries. For example, a fraction of the snappers around marine reserves in New Zealand show strong site fidelity and respond swiftly to protection, while the remainder make longer seasonal movements that take them into fishing grounds [9]. A similar pattern has been observed in at least five commercially important South African shore fishes. For these species approximately 67-93% of individuals were recaptured within 1km of their original tagging site, whilst the rest moved greater distances of tens or even hundreds of kilometres [27]. Reef fish tagged in the Discovery Bay Marine Reserve, Jamaica, showed contrasting movement patterns within species, with some individuals repeatedly caught at the same place within the reserve, whilst others were recaptured tens of kilometres away [28].

For species with even larger scales of movement, marine reserves can still be valuable, offering protection at vulnerable stages. Many migratory species aggregate or pass through migration bottlenecks where they become particularly vulnerable to fisheries [29]. Throughout the world overfishing is eliminating spawning aggregations of snappers and groupers [30]. In the US Virgin Islands, protecting a spawning aggregation site for the grouper *Epinephelus guttatus* led to swift increases in average fish size and in numbers of males in this hermaphroditic species [31], despite covering just 1.5% of the fishing grounds [32]. There is new evidence that highly mobile species like cod may home to specific coastal spawning sites and would benefit from reserve protection in a similar way [33] (J. Hutchings pers. comm.). Even highly migratory species, like sharks, tuna and billfish, could benefit from reserves targeted to places where they are highly vulnerable, such as nursery grounds, spawning sites or aggregation sites like seamounts

[34]. Marine reserves could also protect migration routes. In the case of blue crabs (*Callinectes sapidus*) in Chesapeake Bay, USA [23], currently only their spawning area is protected, but including a deep-water migration route taken by females to spawn could improve the sustainability of the fishery.

Research on marine reserves is revealing how pervasive the effects of fishing are on marine ecosystems. Since the nineteenth century, fisheries scientists have known that exploitation reduces populations, decreases average body size, contracts population age structures and alters species composition. But the degree to which marine ecosystems have been transformed by fishing is surprising us [35]. Rebounding populations in reserves make it clear that fishing has greatly depressed densities and sizes of exploited species. In Fiji, clams in closed areas have reached sizes not seen for three generations [20] (Box 2). Around Merritt Island National Wildlife Refuge, black drum are reaching sizes previously seen only in faded photographs from early last century (Box 3). Furthermore, reserves are showing how entire habitats have been transformed by fishing. In New Zealand and Tasmanian reserves there have been cascading effects of protection. Populations of sea urchins have declined as their predators (fish and lobsters) have grown, transforming overgrazed urchin barrens into kelp forest [36, 11, 37]. Similar effects have been observed in Californian reserves [38]. In Chile, the recovery of a predatory gastropod in closed areas reduced densities of herbivorous gastropods, causing bare rocky shores to be transformed into seaweed-covered rocks [39]. Refuges from fishing are increasing seascape diversity.

What are the magnitudes and scales of fishery benefits from reserves?

There is good evidence that fisheries have benefited through spillover of juveniles and adults, and export of eggs and larvae. Tagging data demonstrate, for example, that crabs in the Sea of Japan [40], lobsters in Newfoundland [24] and New Zealand [25], bream in New Zealand [41] and reef fish in Kenya [42] all moved between protected and fished areas.

The first sign that reserves are increasing catches in adjacent fishing grounds is often people fishing close to reserve boundaries. Eight years after the Mombasa Marine National Park in Kenya became fully protected, catches nearby reached three times more than those further away and senior fishers claimed these fishing spots for themselves [42,43] (L. Rodwell, PhD thesis, University of York, 2001). Marker buoys for lobster pots ring the boundaries of the Leigh Marine Reserve in New Zealand, the Bicheno Reserve in Tasmania and the Anacapa reserve in California's Channel Islands [2]. Bohnsack and Ault [18] found lobster pots set preferentially close to the boundaries of the Sambos Ecological Reserve in the Florida Keys. However, not all studies suggest spillover occurs. Experimental fishing CPUE of blue cod within New Zealand's Long Island-Kokomohua reserve increased four fold after 7 years of protection but remained the same in control sites 1-5km away [10].

Potential scales of spillover vary across species and ecosystems. Fish tagging and movement data from coral reefs suggest spillover will typically extend a few hundreds of metres to a few kilometres from reserves [44]. By contrast, studies quoted above suggest spillover can reach tens to hundreds of kilometres for more mobile species in systems such as estuaries, rocky reefs and continental shelves.

There is less direct evidence for larval export from reserves to fishing grounds but some of the best examples come from stocks that were severely depleted prior to reserve establishment. In Chile a 3 year closure of the squat lobster (*Pleuroncodes monodon*) fishery led to a dramatic increase in biomass, and re-expansion of the species by more than 50km into areas previously fished out [45]. This was probably driven by larval dispersal, as was the recovery of clams in fishing grounds in Fiji [20] (Box 2) and of scallop populations around closed areas on Georges Bank [19] (Box 1). Until only recently, it was thought that ocean currents would transport most offspring spawned in reserves far beyond their boundaries. A broad array of new evidence – biogeographic, genetic, chemical, behavioural and oceanographic [45] – suggests that many larvae could be delivered close to reserves, as near as a few hundred metres for Fijian clams, and a few tens of kilometres for Georges Bank scallops. If local retention is the rule rather than the exception, both spillover and larval export could enhance local fisheries and ensure that protected populations are self-sustaining.

Some studies have directly examined changes in catches adjacent to reserves. Roberts *et al.* [16] found that in 5 years, CPUE of fish traps increased by 46-90% in fishing grounds around a network of reserves in St Lucia. A similar effect was reported from Nabq, Egypt, where CPUE from the trammel net fishery increased by 66% after 5 years protection of a series of reserves [21]. In the Philippines, CPUE of the line fishery around the 0.74km^2 Apo Island Reserve increased ten-fold over 20 years of protection [47]. Fishers in Fiji reported a doubling in catch per unit effort for clams outside their closed area [20] (Box 2). Kelly *et al*. [48] found that lobster catches close to the Leigh Marine Reserve in New Zealand were more variable than those from areas further away, but large catches were more common. Closures on Georges Bank have brought the scallop fishery back from the verge of collapse and show that reserves can work at large scales and for industrial fisheries (Box 1).

How large should reserves be?

Examples in this review show that reserves and closed areas work well across a size range spanning less than 1km^2 to more than 5,000km^2. The key to success is matching reserve size to the scales of movements of the organisms they are designed to protect. For sedentary animals living on coral reefs, reserves of less than a kilometre across have augmented local fisheries, especially where established in networks [16, 21, 47]. For more mobile estuarine fish, reserves in Florida (16 and 24km^2) have sustained spillover to local recreational fisheries for decades. Three closures totalling 17,000km^2 on Georges Bank have helped turn around long-term declines of several important exploited species (Box 1).

The overall scale of protection is as important as the size of reserve units. While closed areas in Newfoundland produced local benefits to lobster catches, at just 2% of fishing grounds, they have had a trivial effect on overall landings. More than forty theoretical and modelling studies have addressed the question of how much of the sea should be protected from fishing (reviewed by Roberts and Hawkins [26]). Depending on the fishery and conditions being considered, they conclude that fisheries benefits require closures of between 10 and 80% of fishing grounds. Most predict maximum benefits with closures of 20-40% (Figure 1). Intriguingly, the most convincing demonstrations of fishery benefits to date are mainly from places where coverage of protected areas falls into this approximate range: Apo Island (10%), Merritt Island (22%), Georges Bank (25%) Nabq (33%), and St. Lucia (35%). For the four locations where data are available to make a judgement, Apo, Nabq, Merritt and Georges Bank, the ‘gold standard’ of higher overall catches with reserves than without, despite a reduced fishing area, appears to have been achieved (to date for scallops only at Georges Bank).

Conclusions

A rapidly growing body of evidence shows that reserves and fishery closures benefit species as diverse as molluscs [49, 19, 20] (Boxes 1 and 2), crustaceans [13, 24] and fish of a wide variety of sizes, life histories and mobilities [2] (Boxes 1 and 3). Benefits develop quickly and build up over long timescales. The examples we describe show reserves work in habitats as different as coral reefs, kelp forests, temperate continental shelves, estuaries, seagrass beds, rocky shores and mangroves [2].

Research on reserves is revealing the profound degree to which people have modified marine ecosystems by fishing. The view is no longer tenable that the sea has escaped the heavy imprint of human dominance that lies upon land. Nature conservation in the oceans cannot be achieved without marine reserves. Fortunately, the evidence available suggests that effective reserves can be designed for any habitat that is fished. At the World Summit on Sustainable Development in 2002, countries agreed ambitious targets for creating national networks of marine protected areas by 2012 and rebuilding overexploited fisheries by 2015. Marine reserves offer a means to deliver on both promises.

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Box 1

Success for large-scale closures in Atlantic fishing grounds

Georges Bank in the Gulf of Maine, USA, once ranked among the most productive fishing grounds in the world. However, intensive exploitation since World War II resulted in fisheries declines and collapses. In 1994, in response to severe fishery depletion, three areas totalling 17,000km^2 were closed to fishing for groundfish (bottom-living fish). They were also closed to all fishing that might catch groundfish incidentally, or damage their habitats, e.g. scallop dredges. Some forms of fishing were still permitted, such as longlining, so the areas were not no-take but still offer important insights into how fully protected areas might work at this scale.

Five years later, the Georges Bank closures, together with a package of cuts in fishing effort introduced at the same time, were hailed as a success for fisheries management [19]. Closed areas significantly reduced fishing mortality of groundfish species, and stocks of haddock (*Melanogrammus aeglefinus*), yellowtail (*Limanda ferruginea*) and witch flounders (*Glyptocephalus cynoglossus*) have increased in particular. Although many key fishery species are still at low densities compared to historical levels, the trends have turned upwards after many years of decline. Cod has responded more slowly to protection, perhaps because they are more mobile, but there are signs that cod biomass is rebuilding too [50,51]. Fishers are beginning to report improvements in catches. One Cape Cod fisherman reported he now travels less than half the distance and catches nearly twice as much cod as he did before the closures [2].

The most dramatic effect of the closures has been on scallops (*Placopecten magellanicus*). Before the closures, fishing had heavily depleted scallops. After five years of protection densities of legal-sized scallops reached 9 to 14 times those in fished areas [19]. Satellite monitoring showed scallop fishing vessels clustering around the edge of the closed areas. Areas of high fishing effort corresponded with the places that biophysical models suggest would have received most scallop larvae exported from closed areas [52,53]. Those models suggest that with a 40-day larval duration, closures supply large regions of the bank as well as replenishing themselves through self-recruitment [54].

The closures are also allowing benthic habitats to recover. Protection from trawling has led to significant increases in the density, biomass, species richness and production of benthic animals [55] (J. Collie pers. comm.) and these effects are likely to be enhancing production of commercial species, leading to long-term sustained benefits.

Box 2

Communities return to traditional closed areas in Fiji

Fiji has a long history of using closed areas for fisheries management. Communities are now returning to this traditional technique to deal with contemporary issues of over-exploitation and diminishing marine resources. In the early 1990s residents of Ucunivanua village consulted with the University of the South Pacific (USP) and the Biodiversity Conservation Network (BCN) for advice on management of their declining catches. Together they put in place several management strategies – replanting mangroves, banning mangrove cutting, coral extraction and poison fishing, obtaining alternative income from a bioprospecting enterprise and setting up a species-specific fishery closure for one of their main fisheries species, the *Anadara* clam.

The clam closure began in 1997 and applied to a 24 ha area of seagrass and mudflat directly in front of the village. The community liased with scientists to design a monitoring programme and have monitored clams inside and outside the closed area since 1997. Results show a dramatic increase in the numbers and size of clams in the closed area after three years of protection and an increase in the number of smaller clams recruiting to fished areas (Figure 2). Clams reached sizes bigger than had been seen for generations. After four years of management, clams had increased in abundance by 13 times in the closed areas and five times in the fished area. CPUE increased and people reported spending half the time fishing to catch the same catch as before [56]. Data collected in 2002 show that after 5 years of protection there have been further increases in clam abundance. Clams are now 19 times more abundant in the closed area and seven times more abundant in the fished area (Ucunivanua community and A. Tawake unpublished data).

The community reported other positive effects, including improvements in the seagrass habitat and the return of species that had disappeared from the area like seahares and stingrays. In response to the effects that they were observing and aware of the temptation for fishers seeking other species to take clams from the closed area, the community decided to make the area completely no-take. The success of the Ucunivanua project for fisheries replenishment, and the high-level of community involvement have led to similar projects developing throughout Fiji. Communities are returning to their traditional practice of *tabu* or closed areas, combining centuries of local knowledge with the latest developments in marine ecology.

Box 3

World record catches cluster around Cape Canaveral reserves

The Merritt Island National Wildlife Refuge at Cape Canaveral, Florida, USA contains two areas (totaling 40km^2) that have been closed to human access and fishing since 1962 for the security of the nearby Kennedy Space Center [57]. An additional 60km^2 area was closed to motorized vessels in 1990 further reducing fishing pressure in the area. Prior to protection there was an intensive recreational fishery.

Johnson *et al*. [57] experimentally fished closed areas after 24-28 years of protection and found more fish and bigger fish compared to nearby exploited areas. Overall CPUE for black drum (*Pogonias cromis*) was 12.8 times higher in unfished areas than fished areas, red drum (*Sciaenops ocellatus*) 6.3 times higher, common snook (*Centropomus undecimalis*) 5.3 times higher, and spotted seatrout (*Cynoscion nebulosus*) 2.3 times higher. The size of red drum, spotted sea trout and black drum were all significantly greater inside the reserves than in fished areas.

Bohnsack [in 16] looked at the effect of these reserves on the adjacent recreational fishery. He found that a much higher percentage of world record size fish were caught close to the reserves than farther away. Within a 200km stretch of coast around the reserves, just 13% of the Florida coast, anglers caught 62% of record-breaking black drum, 54% of record-breaking red drum and 50% of record-breaking spotted seatrout, but only 2% of record common snook. The first three game fish are year-round residents of the refuge, whereas snook is at its northern range limit and leaves in winter [57]. The rate at which each species responded to protection corresponded closely to their longevity. For spotted sea-trout (longevity 15 years) there was a post-protection lag in appearance of record fish of 9 years, for red drum (longevity 35 years) 27 years and for black drum (longevity 70 years) 31 years.

By the end of the 1980s the rate of accumulation of new records in spotted seatrout slowed, but continued to accumulate for the longer-lived drum species. Since the mid-1980s most Florida records for both these species have been recorded close to the refuge. Captures of record fish around the refuge indicate that spillover is occurring. A tagging study at the site showed that common snook moved on average 148km, red drum 47.6km, black drum 47.7km and spotted seatrout 10km [58].

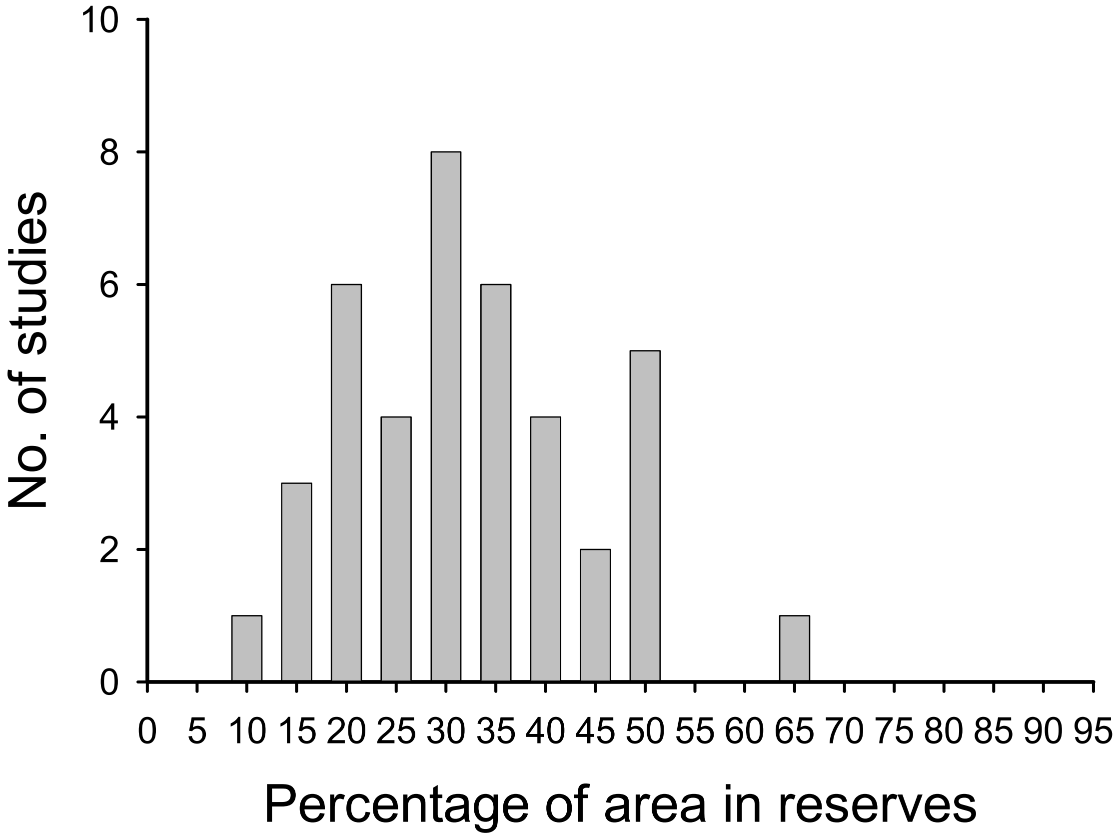

Figure 1 (main text): Frequency distribution of the fraction of fishing grounds recommended to be included in marine reserves. The figure is based on 40 studies (mainly theoretical) that examine the question how much area should be protected from fishing. The data point for each study was derived by first obtaining the range of estimates over which some measure or measures of reserve performance were maximized/optimized/achieved and then taking either the mid-point or, where this was different, the point of greatest benefit from within that range. Literature included in the survey is available on request from the authors.

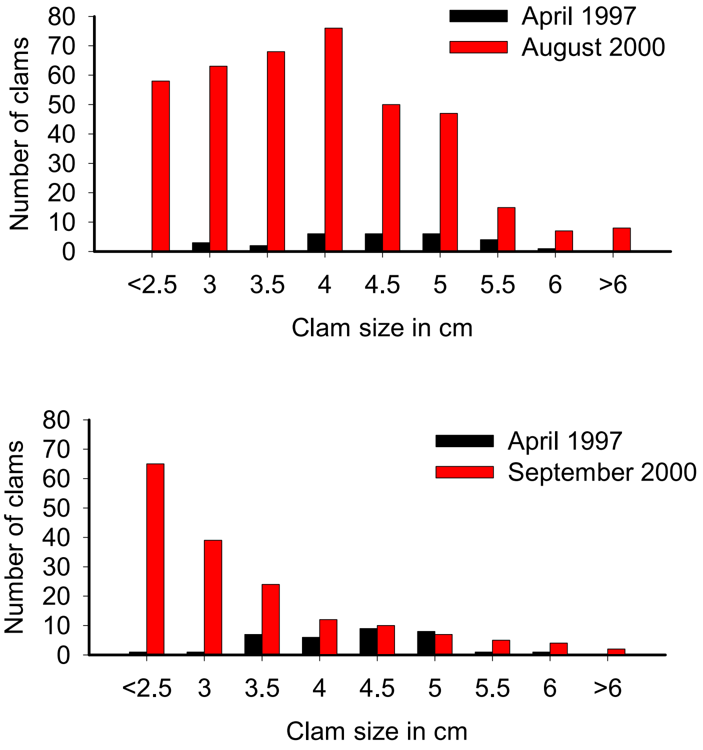

Figure 2 (to be presented in Box 2): The number of clams counted in 50 1m^2 quadrats in each size class in the closed area (top) and in the adjacent fished area (bottom) in 1997 when the closed area was established and in 2000 after 3 years of protection, in Ucunivanua, Fiji. Data collected by the Ucanivanua community monitoring team. Reproduced with permission from Tawake *et al*. [2].

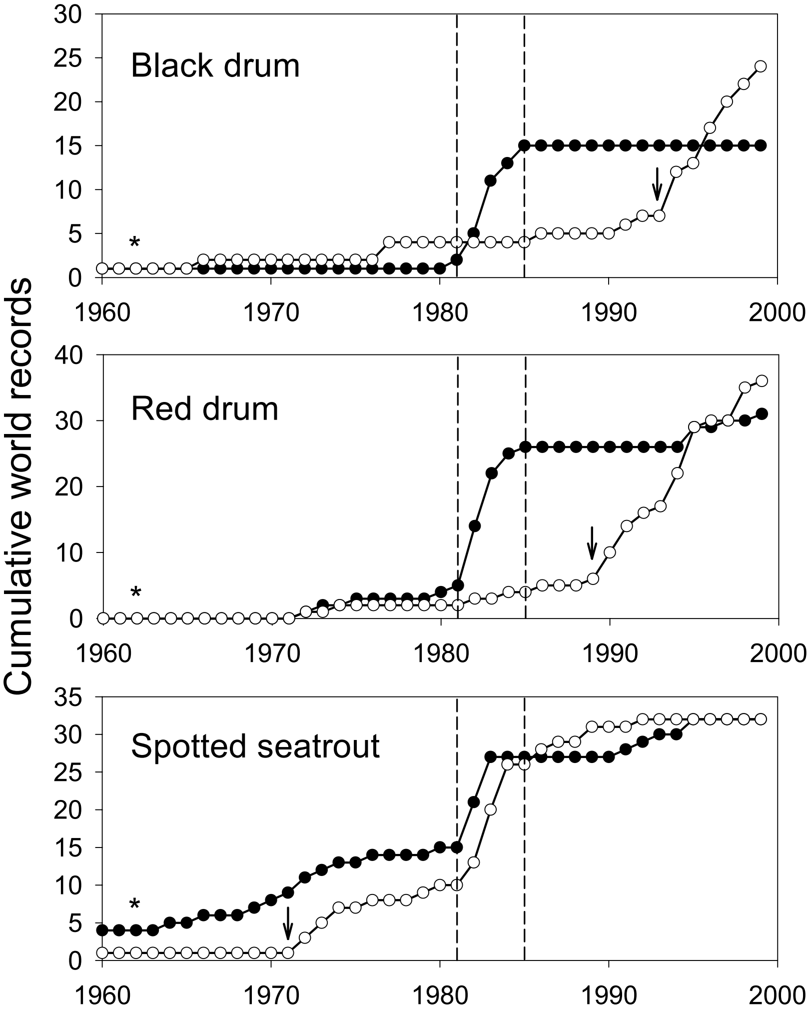

Figure 3 (to be presented in Box 3): Cumulative world records for black drum, red drum and spotted seatrout in the 200 km coastal section adjoining the Merritt Island refuge (open circles) and records from rest of Florida (filled circles). Asterisks show time protection began. Dashed lines show period following introduction of new size class regulations and the arrow shows when there was a rapid increase in accumulation of new records for each species. Reproduced with permission from Roberts *et al* [16].