The value of oceanic marine reserves for protecting highly mobile pelagic species: Coral Sea case study

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Executive summary

This paper reviews the value of marine reserves for protecting migratory and highly mobile pelagic species. Three common arguments used by critics of marine reserves were considered, and the proposed Coral Sea marine reserve was highlighted as an example of how these challenges could be met. Comparisons were made with the UK's recently established large-scale no-take marine reserve in the Chagos Archipelago. The major findings of this review are as follows:

- Recent scientific findings support the idea that large pelagic species benefit from marine reserves, because:
  - Protecting even a part of species' range or life cycles, especially critical habitat areas which function as important feeding or breeding grounds, reduces overall population mortality. Partial protection works best in a coordinated approach for protection, including no-take marine reserves and areas of limited fishing effort;
  - Pelagic species are not uniformly distributed, but tend to aggregate around bathymetric and hydrographic features that are predictable in space and time, making the most beneficial design of pelagic reserves possible; and
  - Even species identified as highly migratory display predictable movement patterns where the majority (70-90 percent) of the population moves no farther than 600 kilometres (km).
- Critics of marine reserves for the conservation of pelagic species have focused on three major issues:
  - Size: Reserves have to be very large to encompass an adequate portion of pelagic species' home ranges;
  - Fisheries management: There is some scepticism about the use of marine reserves as a fisheries management tool, with concerns about displaced fishing effort; and
  - Governance: There is concern that arranging governance and enforcement beyond one country's exclusive economic zone (EEZ) is too challenging.
- The proposed Coral Sea marine reserve is ideal to surmount these challenges and take advantage of the benefits, in the following ways:
  - Size: The proposed reserve encompasses almost 1 million km^2, making it large enough to protect a significant portion (if not all) the home ranges and life cycles of many pelagic species that reside within it. It is large enough to also encompass a large variety of bathymetric and hydrographic features that provide key habitat for pelagic species at vulnerable times (feeding and breeding).
  - Fisheries management: The Coral Sea marine reserve is being proposed for broad ecosystem conservation benefits, not as a fisheries management tool. Its history of relatively low exploitation by fisheries means that pelagic, reef and deep-sea ecosystems are relatively undisturbed, making them strong candidates for conservation to prevent future exploitation, and displaced fishing would be minimal. The permanent closure of the Coral Sea would partially or wholly protect populations of species that are subject to overexploitation elsewhere along their range.

- Governance: The proposed Coral Sea marine reserve lies entirely within Australia's EEZ, making negotiations with neighbouring countries unnecessary. Precedents for managing large marine reserves exist in Australia, and the proposed reserve design (a single large no-take area) is the most cost-effective management option.

Introduction

The open ocean, long considered invulnerable, is under increasing pressure from human impacts[1,2]. As coastal fisheries become depleted, and technological improvements allow fishing vessels to venture farther offshore, large migratory marine species have become more intensely exploited[3,4]. More than 10 years ago, researchers reported that "almost 70 percent of fished stocks are listed as 'fully fished, overfished, depleted, or recovering' "[5]. Numerous heavily exploited species are now of conservation concern, including tuna, billfish and sharks[3,6-8]. For instance, almost all sharks recorded by Baum *et al.* (2003)[3] underwent a 50 percent decline over the 15 years of their study. While marine reserves have steadily increased in coastal areas[9], there is still a lack of adequate protection for pelagic ecosystems worldwide[1,4].

Marine reserves are considered the best conservation tools available to protect marine species and habitats from exploitation[10]. However, the global percentage of area protected in marine reserves is less than 1 percent[11], well below the proportion needed to adequately represent all biogeographic zones[5,12]. Ideally, marine reserves would maintain or restore native species diversity, habitat diversity and heterogeneity, keystone species and connectivity[13]. Diverse and complex habitats promote species diversity[14-16], which in turn affects productivity[17], resistance to and recovery from disturbance[18], stable food web dynamics[6,19] and the capacity to fill all the roles required for a functioning ecosystem even if individual species disappear[20]. Keystone species, or species that can affect whole ecosystems through changes in their abundance[6,21], and connectivity between habitats and populations are also considered critical to the persistence of ecosystems in the face of stressors[16]. The benefit of no-take marine reserves to the abundance and size of sedentary species, especially those with a history of exploitation, is well-documented[22-24]. Despite gaps in knowledge and persisting doubts about their effectiveness in protecting pelagic and migratory species[25], increasing evidence suggests that marine reserves can also benefit these highly mobile species[26-28].

A recent increase in the establishment of very large marine reserves that encompass pelagic and deep-sea ecosystems mirrors the positive shift in the perception of their usefulness[29]. The proposed no-take Coral Sea marine reserve would be one of the world's largest, covering around 1 million km^2 between the seaward edge of the Great Barrier Reef Marine Park and the border of Australia's EEZ[30]. The proposed reserve aims to protect geological, ecological, cultural and heritage values represented within the area[30]. The Coral Sea is regionally important, providing breeding and spawning grounds for a number of migratory species, nesting habitat for seabirds and turtles, and dispersal stepping-stones for marine species between the Pacific and the Great Barrier Reef. There is some concern that this reserve would not adequately protect highly mobile and migratory pelagic species, but parallels exist with other large-scale marine reserves where the protection of pelagic species has been one of the key goals[27].

This paper reviews scientific research that assesses the benefits of marine reserves for protecting migratory and highly mobile pelagic species. This review also evaluates the case of the proposed Coral Sea marine reserve, and considers the three most common arguments against marine reserve establishment in the context of pelagic species protection. Because of similar issues, comparisons are made with the UK's recently established large no-take marine reserve in the Chagos Archipelago.

Positive effects of marine reserves for pelagic and migratory species

Positive, measurable marine reserve effects on pelagic species exist[3,31-33], including for large migratory species such as marine mammals and large predators[32,34-36]. The protection of such species over their whole annual range may not be realistic, but marine reserves can be used to protect them at highly vulnerable stages of their life cycles by encompassing seasonal breeding or feeding grounds, or key parts of their migratory routes[34,37-39] , all habitats critical to the survival of the species (critical habitat)[40]. Because highly mobile species are often also the most heavily exploited, they may receive some benefit even from small marine reserves, although the probability of adequate protection increases with increasing reserve size[28]. Spawning aggregations in particular are increasingly shown to be temporally predictable, and therefore both vulnerable to exploitation and responsive to protection[23,36,41,42]. Protecting vulnerable areas such as breeding or spawning grounds can result in a greater source of larvae or young to the exploited part of the population, resulting in improved breeding success and lower mortality overall[36,39,43]. Some researchers have suggested that protecting at least 50 percent of a species' total habitat would afford it adequate protection[43,44], while others argue that for species that undertake extensive migrations, spatial protection must be coupled with strict harvest quotas[45].

It is generally agreed that one large reserve is more effective for protecting wide-ranging species than a number of small reserves, even if they protect the same overall percentage of a region[46]. A review of marine reserves in 1999 concluded that large migratory species could not be protected with small reserves, where the largest reserve measured 350 km^2 [5]. In contrast, a later review of marine reserve success included reserves in excess of 1,000 km^2 and found that populations of lobsters, snappers and other fish with large seasonal movements of up to 1,000 km[47] did benefit substantially, even if the reserves encompassed only a part of their home range[23].

Critics argue that marine reserves cannot benefit mobile commercial species and are only appropriate for small-scale fisheries in tropical regions[23,48]. The argument against pelagic marine reserves is driven by the notion that they don't work as fisheries management tools; however, their capacity to protect ocean biodiversity is less disputed[49]. Protection for pelagic species already exists in some places (see also Hooker and Gerber 2004[34]), including:

- A number of temporary spatial closures or bans on specific gear types to protect pelagic and migratory stocks in the high seas by regional fisheries management organisations around the world[50];
- Three areas totalling 17,000 km^2 in the Georges Bank, Gulf of Maine, partially closed to fishing[23];
- The Indian Ocean and Southern Ocean Whale Sanctuaries[50],

- Temporary closures by the Mexican government of fixed areas to commercial longlining off the coast of Baja California[32];
- The seasonal protection of southern bluefin tuna habitat off eastern Australia[51];
- Cetacean feeding, migration or calving areas in the Mediterranean Sea, the Great Australian Bight off southern Australia and the Southern Ocean[34,45,52,53];
- Four areas that exclude certain fishing methods (especially purse seining) totalling 1.2 million km^2 stretching 7,000 km from French Polynesia to Palau, established by western Pacific island nations[54];
- The 356,893-km^2 Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands;
- The 246,000-km^2 Mariana Trench Marine National Monument in the northern Mariana Islands, with 17 percent closed to fishing; and
- The 544,000-km^2 Chagos Protected Area in the Indian Ocean[29].

The current lack of data from large oceanic marine reserves means that some of the evidence of their positive effects for pelagic species comes from modelling studies (Table 1)[3,55]. However, the most compelling proof comes from what is termed an "unintended experiment": Fisheries catch data were compiled after a large area of the North Sea (575,000 km^2) had been closed to fishing during the six years of World War II[35]. This study showed conclusively both increased abundance in pelagic species and larger proportions of older fish. In a more recent study, the protection of billfish from longlining in a part of their range off Baja California resulted in an overall population increase of up to 22 percent[32]. The recovery of whales following the combination of reduced whaling and the establishment of large whale sanctuaries also highlights the benefits of marine reserves that cover only parts of species' ranges[56,57]. More recent reviews and meta-analyses have found increasing empirical evidence that highly mobile and large-bodied species exploited by fisheries tend to benefit from marine reserves of varying size[26,33,37].

Table 1. Summary of studies predicting marine reserve benefits for pelagic and migratory species, using a variety of methods.

Source (method)	Location	Species	Summary of findings
Clark (1996)[44] (discussion paper)	Global	All exploited species	- Marine reserves need to include up to 50% of a population or home range in order to protect a species from overfishing.
Lauck *et al.* (1998)[43] (modelling)	Hypothetical	Hypothetical	- Marine reserves need to include up to 50% of a population or home range in order to protect a species from overfishing.
Roberts and Sargant (2002)[36]	Hypothetical	Hypothetical migratory fish	- Protecting important aggregation areas has a disproportionate effect on

Source (method)	Location	Species	Summary of findings
(modelling)			entire populations of highly mobile and migratory species.
Baum *et al.* (2003)[3] (modelling)	Northwest Atlantic	Sharks	- Priority areas for shark conservation are highlighted. - Population benefits for sharks with fishing closures of different areas are modelled. - Marine reserves coupled with reductions in fishing effort have positive effects on sharks and other large pelagic predators.
Gell and Roberts (2003)[23] (review)	Global	All species	- Highlights reversal of notion that mobile species cannot be protected by marine reserves. - Even for highly mobile species, a portion of the population may remain within a small home range - Protecting migration bottlenecks, nurseries, spawning or feeding aggregation sites can benefit even highly migratory species.
Worm *et al.* (2003)[31] (modelling)	Northwest Atlantic	Pelagic species, primarily predators	- Identify pelagic diversity hot spots associated with productivity and habitat features. - Protecting hot spots from fishing has large benefits for pelagic populations. - Identify pelagic predator diversity hot spot in Great Barrier Reef/Coral Sea area.
Willis *et al.* (2003)[26] (empirical, modelling)	Northern New Zealand	Snapper (*Pagrus auratus*)	- Density and size of snapper increase inside marine reserves, despite its high mobility.
Hooker and Gerber	Global	Predators and megafauna	- Marine reserves are beneficial for protecting predators and

Source (method)	Location	Species	Summary of findings
(2004)[34] (discussion paper)			other megafauna (e.g., cetaceans, seabirds). - Present tools and approaches for enhancing marine reserve effectiveness.
Micheli *et al.* (2004)[28] (meta-analysis)	Global	All species	- Highly mobile species benefit from marine reserve protection.
Palumbi (2004)[37] (review)	Global	All species	- Is ambivalent about the value of marine reserves for migratory pelagic species but states that "If fishing effort is not displaced, then the impact of reserves on highly migratory species is similar to the effect of decreasing fishing effort by the same percentage as the percent area dedicated to reserves."
Hyrenbach *et al.* (2006)[58] (empirical)	Central California	Black-footed albatross (*Phoebastria nigripes*)	- Advocates protecting albatross foraging grounds, even though these comprise only a part of their overall range.
Louzao *et al.* (2006)[38] (empirical, modelling)	Balearic Islands	Balearic shearwater (*Puffinus mauretanicus)*	- Marine zoning measures can benefit populations of far-ranging seabirds by extending protective measures beyond their breeding colonies.
Alpine and Hobday (2007)[55] (modelling)	Eastern Australia	Pelagic, migratory and other species targeted by fisheries or of conservation concern	- Quantified the area requirements of pelagic protected area networks to protect pelagic species (target and non-target). - Area requirements ranged from 7 to 26% of the region for adequate protection of pelagics.
Pichegru *et al.* (2009)[39] (empirical)	Benguela upwelling region	Cape gannets (*Morus capensis*) and African	- Measured overlap between seabird feeding and commercial fishing grounds.

Source (method)	Location	Species	Summary of findings
		penguins (*Spheniscus demersus*)	- Marine reserves in bird-feeding hot spots is likely to increase the birds' breeding success.
Beare *et al.* (2010)[35] (empirical)	North Sea	North Sea gadoids	- Large North Sea area unfished during World War II. - Large benefits to exploited fish, including migratory species. - Older fish benefit fastest and in greatest proportion, creating a "Mexican wave" in numbers of subsequent generations.
Claudet *et al.* (2010)[33] (meta-analysis)	European marine reserves	Fish	- Density and size of species targeted by fisheries increase inside marine reserves, even highly mobile species.
De Juan and Lleonart (2010)[4] (modelling)	Mediterranean	All pelagic species	- Identifies habitats critical to pelagic species in the Mediterranean. - Advocates for marine reserve protection of pelagic species.
Jensen *et al.* (2010)[32] (empirical)	Baja California	Striped marlin (*Kajikia audax*)	- Temporary closures of Mexico's EEZ to long-lining (1977–1980, 1984–1985) caused increase in striped marlin, despite its range extending outside the closed area.
Koldewey *et al.* (2010)[27] (review)	Global	All species	- Increasing evidence that even partial protection of highly mobile and migratory species is beneficial. - "Highly migratory" species may be based on long-range movements of a few individuals, while most of the population remains within a home range.

The Coral Sea plays a regionally important role for South Pacific pelagic fish stocks. It hosts spawning aggregations of tuna, billfish[59-61] and other large pelagic fish[62], and contains nesting grounds for marine turtles and seabirds[63,64]. It is one of the few oceanic areas that has retained a high diversity of large oceanic predators[31] that are heavily exploited elsewhere along their range[65]. The wide range of bathymetric features such as reefs and seamounts attracts migratory species, including seabirds[66] and cetaceans[67]. The proposed Coral Sea marine reserve, covering an area of around 1 million km^2, would ensure that a high proportion of the key areas in the life cycles and migration pathways of many pelagic species are protected (see Appendix 1).

Positive ecosystem-level effects of pelagic marine reserves

The capacity for well-designed marine reserves to meet the objectives of maintaining or restoring species, habitats and connectivity[13] is increasingly well-documented, especially for shallow-water environments[10,24]. When species diversity is protected, for instance, rates of resource collapse decrease and recovery potential, stability and water quality increase, sometimes exponentially[17]. Most scientists agree that marine reserves protect habitats and biodiversity[68,69] by reducing stressors such as extraction[55], making ecosystems more resilient and therefore better able to withstand the more pervasive effects of climate change and pollution[17,70-72].

Because of the vast extent of oceanic ecosystems and the increased understanding of their value, it is now believed that pelagic marine reserves are rapidly becoming a reality in the planet's "last frontier of conservation management"[11, 28,54,73], although their implementation may be both costly and difficult[74]. Large-scale pelagic marine reserves have the capacity to protect greater diversity, larger habitats and entire trophic webs and ecological processes[29,34]. As well as pelagic habitats, they would include deep-sea ecosystems that are poorly understood and yet at risk from activities such as trawling, oil and mineral exploration, and sea dumping[71,73,75]. Protecting entire bioregions has the benefit that pathways of connectivity will be preserved without the need for complex conservation planning to establish a marine reserve network[16].

The proposed marine reserve in the Coral Sea would encompass four large-scale bioregions[62], including terrestrial, pelagic, shallow, deep and abyssal ecosystems[62]. The cessation of fishing would not only benefit the numerous target species, but also the large number of species caught as bycatch[76]. The coral reefs in the Coral Sea are already vulnerable to high temperature anomalies that can cause coral bleaching and death; some of these reefs appear more vulnerable than others[77]. Studies of genetic connectivity[78,79] indicate that the Coral Sea might contain the entire genetic stock of some species, as well as the stepping-stones of dispersal between the wider Pacific Ocean and the Great Barrier Reef[80]. Preliminary research suggests that the Coral Sea's deep-sea habitats are vulnerable, patchy and important for deep-diving pelagic species[81]. A permanent closure would safeguard critical habitats such as breeding and feeding hot spots, support the resilience of ecosystems and connectivity pathways, and therefore enhance the persistence of pelagic populations.

Predictability of bathymetric and hydrographic features

Despite the perception that the open ocean is relatively featureless and large species move through it more or less at random, there are persistent and predictable bathymetric and hydrographic features[3,31,82]. Hyrenbach *et al.* (2000)[82] distinguished between three types of oceanic features that can be mapped: 1) static systems, defined by topographic features; 2) persistent hydrographic features, such as currents and frontal systems; and 3) ephemeral habitats, shaped by wind- or current-driven upwellings and eddies. All three types of features are known to attract aggregations of marine life and may be identified by analysing the foraging distribution of higher predators[82] or by making use of sophisticated real-time imagery[11]. The tendency for pelagic species to aggregate in predictable seasons and areas of ocean has made them highly exploitable, and predicting the location of aggregations of commercially valuable species has been important in fisheries oceanography[55]. Even highly migratory species have been found to travel along predictable pathways defined by topographic or oceanographic features[83]. In fact, the predictability of movements and aggregations of terrestrial migratory species has already been applied to the protection of migratory species on land and is considered viable in the open ocean[733].

Topographic features such as shelf breaks, canyons and seamounts alter the water flow above them, causing highly productive plankton blooms or swarms[82]. Turbulent water flow in the lee of islands and emergent reefs also serves to retain the planktonic food sources of pelagic fish[84]. These features have been shown to act as highly effective natural aggregation devices for tuna and other migratory species, primarily for feeding[85,86], but also for breeding[87]. Hydrodynamic features such as eddies, currents, upwellings, downwellings or fronts are also areas of high productivity, attracting species from all trophic levels[82]. Temperature fronts, or water mass boundaries, are well-known as biological hot spots and migration corridors[88,89]. The dynamic nature of these features has served to fuel the argument against spatial closures[51,55], but many of these features are predictable in space and time and can be tracked remotely[11].

The Coral Sea contains more than 30 emergent reefs and atolls, part of a major seamount chain, four major plateaus and a series of troughs, slopes, canyons and abyssal plains[62,90]. Major currents, gyres and eddy systems interact with these bathymetric features, creating a complex pattern of hydrodynamic regimes with the potential to support numerous hot spots of pelagic diversity[91]. Most of these features and communities remain to be studied, but existing research has shown increased productivity in the lee of islands and reefs[84] and an increase in the abundance of the larvae of some tuna and billfish species near reefs and islands[92]. A further study has indicated that broadbill swordfish may set up resident populations in the vicinity of seamounts, and favourable conditions for this exist in the Coral Sea[60]. Sophisticated remote sensing tools exist that can map the position, movement and extent of areas likely to attract aggregations of pelagic life[11]. Protecting the entire Coral Sea would ensure the inclusion of these features, and the large size of the reserve would allow for seasonal or annual movements of the more dynamic fronts, eddies and currents.

Key arguments from marine reserve critics

Argument 1: Reserve size and migration distance

A key argument against oceanic marine reserves is that they would need to be exceedingly large to adequately protect migratory species[74]. It is argued that even species that habitually reproduce or feed in an area of ocean do not exhibit the level of site fidelity needed for a marine reserve. For instance, Kaplan *et al.* (2010)[74] argue that the tropical skipjack tuna (*Katsuwonus pelamis*) does not undertake consistent feeding or breeding migrations, making it difficult to establish a reserve for its protection in the right place. Similarly, the population of whale sharks protected by the Ningaloo Marine Park is in decline, due to intensifying threats elsewhere along its range[93]. However, it has previously been shown that even protecting one part of a tuna's home range or life cycle can have an overarching positive effect on its overall stocks[94]. A modelling study showed that because highly mobile species are often also the most heavily exploited, they are most likely to benefit from marine reserves, with larger reserves affording greater protection[28]. Partial protection for migratory species cannot be considered futile[4,95].

In fisheries management, the phrase "highly migratory" can be derived from the long-range movements of a few individuals within a population, with studies of tuna mobility demonstrating they would benefit from national-level closures[94]. For instance, in assessing the efficacy of the Chagos marine reserve for the protection of tuna stocks, Sheppard (2010)[22] questioned the distances implied by "highly migratory" and found that the average distance travelled by tagged tunas meant that they would spend relatively little time outside the reserve. Even for a species shown to be highly migratory (the striped marlin [*Kajikia audax]*), reduction in fishing pressure over a small part of its range resulted in measurable improvement[32]. Another study cautions that long-range movement may be undertaken by only some members of a population and that generalizations about the mobility of the entire population may be inappropriate[26].

Applying this argument to the Coral Sea, migration distances reported in the available literature were collated for the pelagic species most targeted by the Eastern Tuna and Billfish Fishery, after Hobday (2010)[96]. If movement data were available, further species were added if they were highly valued by the game-fishing industry or often caught as bycatch (Table 1). Species with the ability to undertake migrations of more than 1,000 nautical miles tend to move between 400-600 nautical miles on average (Table 2). While this may take them into the EEZs of other Pacific nations, there is a high likelihood that they may spend 50 percent of their time inside the Coral Sea, effectively complying with the guidelines set up by Clark (1996)[44] and Lauck *et al.* (1998)[43] for adequate protection. Sibert and Hampton (2003)[94] state that while international arrangements are ideal, protection of tuna stocks within an individual country's EEZ is also highly effective.

Table 2. Recorded movement distances for species caught by the Eastern Tuna and Billfish Fishery, ranked in order of importance after Hobday (2010)[96]. Also added are five species (below the line) that feature strongly in fisheries, as target or bycatch species. For a more comprehensive list of pelagic and migratory species that are exploited in the Coral Sea or elsewhere, and may therefore benefit from protection, see Appendix 1.

Species	Info	Reference
Yellowfin tuna	34 tunas tagged in the Coral Sea and recaptured, most along the New South Wales (NSW) coast within 200 nautical miles (nm) of release; longest straight-line distance between release and recapture was 569 nm after 9 months.	Hampton and Gunn (1998)[97]
	273 tunas tagged by game fishers, most recaptured within the Australian Fishing Zone less than 600 nm from release.	
	Most tunas tagged by the Australian Commonwealth Scientific and Research Organization (CSIRO) in the Coral Sea were caught close to the release area.	
	Median lifetime displacement of 336-376 nm, mostly northeast into EEZs of other Pacific Island nations.	Sibert and Hampton (2003)[94]
	Average distance travelled for all individuals recaptured from 2006 to 2008 was 247 nm.	Industry & Investment (I&I) NSW (2009)[98]
Broadbill swordfish	Median movement of tagged fish was 744 km.	Sedberry and Loefer (2001)[99]
	Average distance travelled during 193 days was 30 ± 43 km.	Sepulveda *et al.* (2010)[100]
Bigeye tuna	Most tuna tagged by CSIRO in the Coral Sea were caught close to the release area.	Hampton and Gunn (1998)[97]
	90% of tuna captured within 150 nm of tagging location.	Clear *et al.* (2005)[101]
Albacore tuna	Two individuals tagged and recaptured: one moved 302 nm, the other 1,727 nm.	I&I NSW (2009)[98]
	Average distance travelled was 859.25	Cosgrove *et al.* (2010)[102]

Species	Info	Reference
	km.	
Dolphinfish	Move distances of up to 440 km.	Kingsford and Defries (1999)[103]
	Average distance travelled for all individuals recaptured from 2006 to 2008 was 112.6 nm.	I&I NSW (2009)[98]
Striped marlin	90% of 360 tagged individuals were recaptured less than 1,000 km from the tagging location.	Jensen *et al.* (2010)[32]
	Mean straight-line distance per fish was 921 ± 264 km.	Holdsworth *et al.* (2009)[104]
	Average distance of 280 nm	Squire Jr. (1974)[105]
	The majority of striped marlin released off Australia have a mean displacement of less than 200 nm (after six to nine months).	Bromhead *et al.* (2004)[106]
	Average distance travelled for all individuals recaptured from 2006 to 2008 was 214.2 nm.	I&I NSW (2009)[98]
Shortfin mako shark	Move between ocean basins, enough to cause a lack of genetic differentiation.	Schrey and Heist (2003)[107]
	Approximately 75% of the makos travelled less than 500 nm from their original tagging location with a mean distance of 398.	Kohler *et al.* (2002)[108]
	Average distance for seven juveniles tracked between six and 45 hours was 55 km.	Sepulveda *et al.* (2004)[109]
	Average distance travelled for all individuals recaptured from 2006 to 2008 was 571 nm.	I&I NSW (2009)[98]
	Tagged off eastern Australia, stayed within the region.	Stevens *et al.* (2010)[110]
Blue shark	82% of recaptured blue sharks travelled less than 1,000 km.	Queiroz *et al.* (2005)[111]
	More than 75% of the blue sharks travelled less than 1,000 nm from their original tagging location with a	Kohler *et al.* (2002)[108]

Species	Info	Reference
	mean distance of 463 nm.	
	Average distance travelled for all individuals recaptured from 2006 to 2008 was 697 nm.	I&I NSW (2009)[98]
	Tagged off eastern Australia, stayed within the region.	Stevens *et al.* (2010)[110]
Wahoo	Can move more than 1,000 km.	Theisen *et al.* (2008)[112]
Skipjack tuna	Median lifetime displacement ranges from 420 to 470 nm.	Sibert and Hampton (2003)[94]
Black marlin	Average short-term movement of five tagged marlin was 277.4 nm.	Gunn *et al.* (2003)[113]
	Average distance travelled for all individuals recaptured from 2006 to 2008 was 727.5 nm.	I&I NSW (2009)[98]
Sailfish	Average distance travelled for all individuals recaptured from 2006 to 2008 was 38.6 nm.	I&I NSW (2009)[98]
Porbeagle shark	More than 90% of tagged porbeagles travelled less than 500 nm from their original tagging location, with a mean distance of 234.	Kohler *et al.* (2002)[108]
Thresher shark	Tagged off eastern Australia, stayed within the region.	Stevens *et al.* (2010)[110]

Argument 2: Fisheries losses and overexploitation

Fishers are typically opposed to the establishment of marine reserves that overlap with their fishing grounds because of the perceived loss of revenue[29,114], even though it has been shown that fishing yield can be equivalent between marine reserves and traditional fisheries management[115]. Closure of large areas to fishing may lead to displacement of fishing effort that will cause overexploitation elsewhere[3,31]. For instance, in a modelling study of the northwest Atlantic, the closure of an area with low to intermediate existing fishing effort simply displaced fishing effort elsewhere—to areas of higher species diversity—and increased the catch rate of most shark species[3].

An economic impact assessment of fisheries closure in the high seas concluded that overall losses would be minimal in comparison with the ecosystem service and biodiversity benefits gained from such protection—it was calculated that the closure of 20 percent of the high seas may lead to the loss of only 1.8 percent of the current global reported marine fisheries catch[116]. It has now been established that marine reserves can export target species into adjacent fisheries, both through the emigration of adults and juveniles and the export of propagules[23,117, 118,119]. This “spillover” effect must be integrated into analyses of displaced fishing effort.

It is unclear whether overexploitation of pelagic species is occurring in the Coral Sea. Global assessments consider the region lightly fished[65], but estimates of catches on the northeast shelf, which include the Coral Sea, have documented large declines in catch rates (Figure 1). Furthermore, a number of species are considered at high risk from Eastern Tuna and Billfish Fishery (ETBF) longlining, most notably longfin mako sharks, crocodile sharks, pelagic thresher sharks, dusky sharks, ocean sunfish, short-finned pilot whales, false killer whales and leatherback turtles[76]. Two commercial fisheries (the Coral Sea Fishery, or CSF, and the ETBF)[i] make up the bulk of the catch in the entire Coral Sea, and the charter fishing industry targets large predators in the Great Barrier Reef Marine Park and Coral Sea[120]. The CSF is small (with 17 licensed operators, a mean gross value of production [GVP] of A$866,000 between 2002 and 2006) and data-poor, making it difficult to ascertain trends and sustainability[121,122]. The lack of good data will make it extremely difficult to calculate the impact of the proposed closure of the CSF[121].

The ETBF also operates within the entire Coral Sea area but extends farther south, and less than one-third of its catch (between 15 and 31 percent in the years 1998 to 2006) comes from the Coral Sea itself (Table 3). The largest catch per unit effort for all species within the Coral Sea comes from its southern edge[123]. Climate change is expected to drive many large pelagic species, including the 14 top species caught by the ETBF, farther south, suggesting that yields for this fishery in the Coral Sea are expected to decline[96].

The potential costs and displaced fishing effort of recreational and charter fishing in the Coral Sea is less well-understood. The sport fishery between Cairns and Lizard Island is highly lucrative, targeting a well-known black marlin spawning aggregation[60]. Game fishing from charter vessels occurs around many reefs and seamounts of the Coral Sea, but data from the long-term Game Fish Tagging Program indicates that between 1989 and 2009, 99.2 percent of more than 18,000 tagged fish were caught in the Great Barrier Reef Marine Park and 0.8 percent in the Coral Sea[124]. It is therefore possible that the risk of displacing fishing effort is small, and that populations of tuna, shark and billfish species that are heavily exploited outside the Coral Sea may benefit from marine reserve protection along this part of their range.

[i] Five fisheries are permitted to operate in the Coral Sea. Additional fisheries to the CSF and the ETBF are the Norfolk Island Fishery, the Southern Bluefin Tuna Fishery, the Eastern Skipjack Fishery and the Torres Strait Island Fishery. Catches from these fisheries are either almost entirely from outside the Coral Sea or the data are absorbed within the ETBF for reporting purposes.

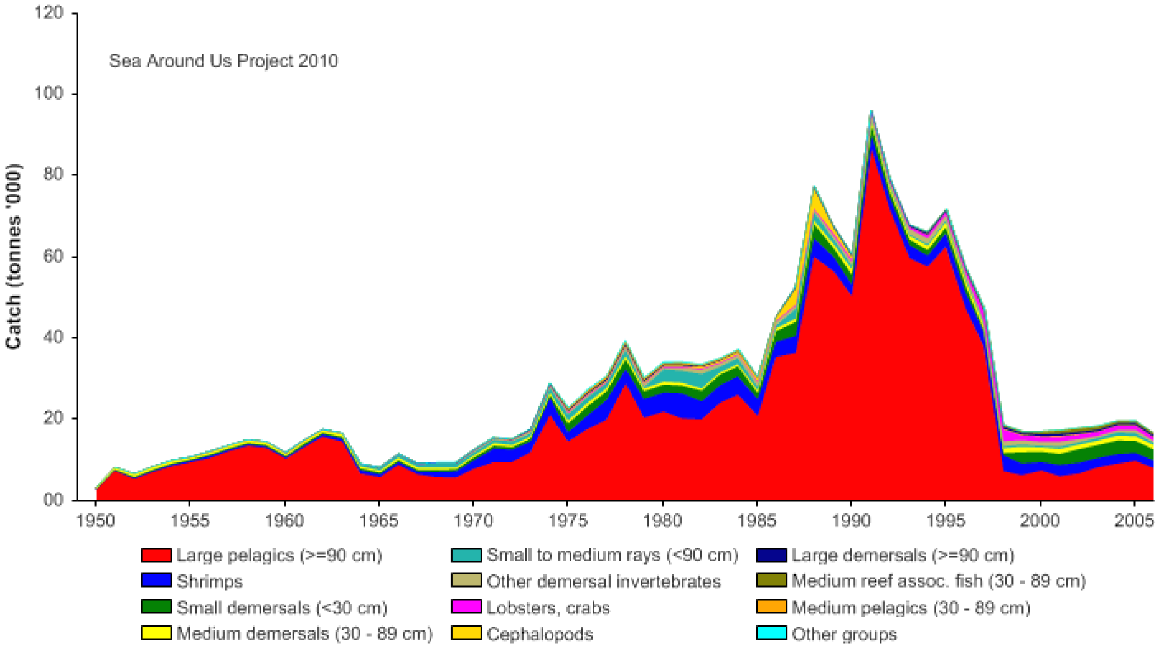

Figure 1. Landings by functional groups on the northeast Australian shelf, which includes the Coral Sea, 1950-2006. From www.seaaroundus.org/lme/40/3.aspx.

Table 3. Catches (tonnes) of the most important ETBF species between 1998 and 2006. Data are split between catches from 25°S north (lying mostly in the Coral Sea), total catch from all areas, and the percent of the catch from above 25°S (%CS)from [123].

Species	Location	98/99	99/00	00/01	01/02	02/03	03/04	04/05	05/06
Yellowfin tuna	Coral Sea	753	258	652	778	856	465	370	463
	Total	2,144	1,306	1,499	2,460	3,390	2,407	1,945	1523
	% CS	35.1	19.7	43.5	31.6	25.2	19.3	19	30.4
Bigeye tuna	Coral Sea	421	196	472	324	338	200	268	137
	Total	897	679	998	1,019	934	769	822	555
	% CS	46.9	28.9	47.3	31.8	36.2	26	32.6	24.7
Broadbill swordfish	Coral Sea	366	216	404	324	211	121	148	127
	Total	1,651	2,081	1,854	2,336	2,175	1,669	1,637	1,447
	% CS	22.2	10.4	21.8	13.9	9.7	7.2	9	8.8
Striped marlin	Coral Sea	50	36	138	150	90	48	23	80
	Total	492	514	717	768	631	574	408	505
	% CS	10.2	7	19.2	19.5	14.3	8.4	5.6	15.8
Albacore	Coral Sea	93	76	91	159	107	64	83	809

Species	Location	98/99	99/00	00/01	01/02	02/03	03/04	04/05	05/06
	Total	404	362	396	663	493	546	620	1584
	% CS	23	20.9	22.9	23.9	21.7	11.7	13.4	51.1
Sharks	Coral Sea	74	52	83	95	42	42	22	18
	Total	222	280	305	336	175	177	134	108
	% CS	33.3	18.6	27.2	28.3	24	23.7	16.4	16.7
Other	Coral Sea	126	45	209	219	129	128	100	143
	Total	334	267	862	756	644	657	546	602
	% CS	37.7	16.8	24.2	28.9	20	19.5	18.3	23.7
TOTAL	Coral Sea	1,884	880	2,050	2,051	1,773	1,068	1,014	1,777
	Total	6,143	5,488	6,631	8,338	8,442	6,798	6,111	6,324
	% CS	30.7	16	30.9	24.6	21	15.7	16.6	28.1

Argument 3: Governance and enforcement

The third key criticism of pelagic marine reserves centres on the costs and logistic constraints of governance, but the greatest concerns are directed toward marine reserves in international waters[4,11,74]. Where a marine reserve is placed entirely within a nation's EEZ, concerns are focused less on governance issues and more on the logistics and costs of management[11]. Large, multiple-use marine reserves such as the Great Barrier Reef Marine Park can offer both a blueprint for the type of surveillance and enforcement required, and a cautionary tale of the effects of insufficient enforcement activity[10,125].

There is still much to be learned about the enforcement of pelagic marine reserves[126]. In remote oceanic areas, large no-take marine reserves are easier to police than multiuse parks or even marine reserve networks[22], and a recent analysis found that larger reserves cost less per unit area than smaller ones[127]. This same analysis examined three potential management scenarios for the Coral Sea (one large no-take reserve, a multiuse park with 30 percent of its area as no-take, and three smaller no-take areas making up 30 percent of the whole area together), and found that a single large no-take area would be the least costly to manage.

The proposed Coral Sea marine reserve would not extend beyond the boundaries of Australia's EEZ, precluding the need for complex international arrangements. Surveillance in this vast and remote area may be challenging, but there is increasing sophistication in vessel-monitoring systems (VMSs) and satellite technology[11]. Additionally, there are existing arrangements and infrastructure that may be used for management activities and compliance monitoring[127] (see also Table 4). As a relatively wealthy nation with an extended EEZ, Australia is in an ideal position to take a leading role in the global protection of oceanic species and ecosystems.

Table 4. Summary table of challenges raised by critics of marine reserves for the protection of pelagic species, with proposed solutions and counterarguments, both general and directly relevant to the Coral Sea. Table reproduced and extended from Game *et al*. (2009) [11].

Issue		Challenges	Solutions and counter-arguments	Coral Sea example
Biological	Many pelagic species are highly mobile, often covering thousands of kilometres annually.	Spatial protection is either impossible across whole ranges or for all life-history stages, or the area required for conservation management would be unreasonably large.	Many threats to pelagic organisms are either site specific or cumulative, and can be reduced through spatial protection[34]. In addition, many organisms either show site fidelity or have relatively small and defined areas of critical habitat within their range or life histories[38,58].	The Coral Sea marine reserve would protect around 1 million km^2 of ocean, including islands, reefs, seamounts, open ocean, abyssal plains, plateaux and canyons. Even highly mobile species have a high probability of spending at least 50% of their life cycle in the Coral Sea (Table 1).
		Regulations or moratoria on gears or catch are more appropriate for limiting incidental capture of threatened pelagic fauna.	Although catch and gear regulations are an important component of pelagic conservation, they have so far proved inadequate in protecting many target and bycatch species[95].	The ETBF still records large quantities of bycatch, and stocks of its primary target species are known to be vulnerable[127].
Physical	The pelagic ocean is characterized by physical processes that are dynamic in space and time.	The environment is too dynamic to be represented in static reserves. Mobile reserves would be too difficult to enforce.	Many important pelagic features are either spatially or temporally predictable[82], so static or dynamic marine reserves need to be designed accordingly[55]. For features with less predictability, mobile fisheries closures have been effectively implemented off eastern Australia based on near real-time predictions	A Coral Sea marine reserve would encompass a number of permanent or predictable bathymetric and hydrographic features known to attract aggregations of pelagic and migratory species[62].

			of pelagic habitat[51]. Governance issues are also addressed below.	
Design	The pelagic ocean is generally data-poor compared with terrestrial or coastal systems.	Lack of data on the complexities of pelagic ecosystems limits the selection and design of marine reserves.	Widespread data sets, especially time-series data on remotely sensed physical and biological features (e.g., chlorophyll), are more abundant than commonly perceived and are useful for marine reserve selection. In contrast to fisheries catch limits, the selection of pelagic marine reserves does not have to rely on full understanding of ecosystem functions.	Remote sensing data for the Coral Sea is available through a number of sources. The general understanding of the Coral Sea's bathymetry (structure of the seafloor), oceanography and ecology is good[62,128].
	There is a lack of well-established design principles to inform the selection of pelagic marine reserves.	Design principles for pelagic marine reserves will need to be developed de novo.	Some existing conservation planning tools and methods can be used in the pelagic ocean (e.g., Marxan), and good case studies are starting to appear. New challenges will lead to novel solutions with broad impact.	One of the primary requirements for the protection of pelagic and migratory species is that a marine reserve be large enough to encompass at least 50% of their home range[44]. The Coral Sea marine reserve would protect around 1 million km^2. This area is highly likely to be adequate for the protection of most pelagic and migratory species that use its habitats.
Governance	Marine reserves might need to extend outside a country's EEZ.	Beyond national jurisdictions there is no legal basis for marine reserves.	Numerous existing international and regional agreements can be exercised to regulate marine reserves in the high seas[27].	The proposed Coral Sea marine reserve does not extend beyond Australia's EEZ[30].

	Exploitation of the pelagic ocean is generally difficult and expensive to observe, and it is therefore challenging to enforce regulations.	Marine reserves will be more difficult and expensive to enforce, especially in developing nations, than traditional catch or gear restrictions.	Widespread adoption of satellite VMSs, and financial support for this in developing nations, will improve remote surveillance.	Australia is a wealthy nation where technology and surveillance operations are, to some extent, already in place[129]. A precedent is in place for the use of existing operations for research and compliance monitoring[127].

Parallels with Chagos/BIOT

The newest addition to a growing list of very large marine reserves is the Chagos Archipelago or British Indian Ocean Territory, referred to by Koldewey *et al.* (2010)[27] as Chagos/BIOT. The ecological rationale behind the establishment of this marine reserve could easily be applied to the proposed Coral Sea marine reserve. Scientific research suggests that with 544,000 km^2 of ocean, reefs and seamounts, the Chagos/BIOT Marine Reserve potentially provides an excellent area for the recovery of shark, tuna and other large predators[27]. Similarly, the Coral Sea is highly likely to be large enough (approximately 1 million km^2) to adequately protect large pelagic predators that are subject to overexploitation elsewhere along their range[130]. Other similarities between the two regions are the relatively intact nature of the entire system, the remoteness of the coral reefs from human impacts, their status as stepping-stones to genetic connectivity between broader regions, their regional importance for threatened and endangered species and the diversity of undersea geological features[27]. These criteria were crucial in driving the protection of Chagos/BIOT[48].

Chagos/BIOT has met with opposition, especially from the tuna fishing industry[22]. Unfortunately, the lack of data about tuna catches within the reserve made it difficult to estimate the potential loss to the industry or the displacement likely to occur into other areas[22,48]. Estimates of the proportion of the Indian Ocean catch coming from the Chagos/BIOT area range from 2 to 6 percent[22]. The proportion of the ETBF catch in the Coral Sea is higher, ranging from 15 to 31 percent between 1998 and 2006. The Coral Sea Fishery operates entirely within the proposed reserve area, but its commercial value is relatively low. Recreational fishers and representatives of the game-fishing industry, rather than the commercial fishing industry, have expressed opposition to the protection of the Coral Sea (I. Zethoven, pers. comm.).

Chagos/BIOT was declared in the first half of 2010 despite a lack of existing information, apart from some fisheries data[27]. In comparison, despite knowledge gaps, the Coral Sea is reasonably well-understood; knowledge of underlying bathymetric and oceanographic features and biological communities has allowed broad ecological patterns and processes to be described or inferred[62]. There is increasing global demand to heed the precautionary principle, especially in marine ecosystems where data are scarce and fisheries decline or collapse has been well-documented[13,43,44,82].

Conclusions

This review has detected a trend in the scientific literature toward greater support for the use of marine reserves to protect migratory and highly mobile pelagic species. Recent research has demonstrated that large pelagic species targeted by fisheries benefit from marine reserves. This is most likely because:

- Even protecting a part of species' ranges or life cycles, especially critical habitat areas which function as important feeding or breeding grounds, can cause a decrease in overall population mortality;
- Pelagic species are not uniformly distributed, but tend to aggregate around bathymetric and hydrographic features that are predictable in space and time, making the most beneficial design of pelagic reserves possible; and

- Even species identified as “highly migratory” display movement patterns where the majority (70 to 90 percent) of the population moves no farther than 600 km.

Critics of marine reserves for the conservation of pelagic species have focused on three major issues. Firstly, there has been a concern that reserves have to be very large to encompass an adequate portion of pelagic species’ home ranges. Secondly, there is some scepticism about the use of marine reserves as a fisheries management tool, with concerns about displaced fishing effort causing overexploitation in adjacent areas. Thirdly, there is a great degree of difficulty associated with arranging governance and enforcement beyond one country’s EEZ .

The proposed Coral Sea marine reserve is ideally placed to surmount the challenges raised. The proposed reserve encompasses almost 1 million km^2, making it large enough to protect a significant portion (if not all) of the home ranges and life cycles of most pelagic species that reside within it. It is large enough to also encompass a large variety of bathymetric and hydrographic features that provide key habitat for pelagic species at vulnerable times (feeding and breeding). It lies entirely within Australia’s EEZ, making difficult negotiations with neighbouring countries unnecessary. Existing marine operations and technology may be used for surveillance and enforcement. The Coral Sea marine reserve is being proposed as a conservation tool rather than a fisheries management strategy. Its history of relatively low exploitation, coupled with its relatively high remaining density and diversity of large pelagic predators, is considered ideal for conservation, as its ecosystems remain relatively undisturbed. Finally, a recent precedent exists: The ecological values leading to the declaration of the Chagos/BIOT marine reserve are also found in the Coral Sea.

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Appendix 1—Migratory and pelagic species of the Coral Sea

This table lists those migratory and pelagic species affected by fishing in the Coral Sea, either as target species or bycatch[76], and may therefore benefit from protection.

Species	Common name	Pressure
Thunnus albacares	Yellowfin tuna	Commercial fishing
Thunnus obesus	Bigeye tuna	Commercial fishing
Xiphias gladius	Broadbill swordfish	Commercial fishing
Thunnus alalunga	Albacore tuna	Commercial fishing
Coryphaena hippurus	Dolphinfish	Commercial fishing
Centrolophus niger	Rudderfish	Commercial fishing
Tetrapturus audax	Striped marlin	Commercial fishing
Isurus oxyrinchus	Shortfin mako shark	Commercial fishing
Prionace glauca	Blue shark	Commercial fishing
Acanthocybium solandri	Wahoo	Commercial fishing
Makaira indica	Black marlin	Commercial fishing
Brama brama	Ray's bream	Commercial fishing
Ruvettus pretiosus	Black oilfish	Commercial fishing
Katsuwonus pelamis	Skipjack tuna	Commercial fishing
Thunnus thynnus	Northern bluefin tuna	Commercial fishing
Tetrapturus angustirostris	Shortbilled spearfish	Commercial fishing
Istiophorus platypterus	Indo-Pacific sailfish	Commercial fishing
Lampris guttatus, L. immaculatus	Moonfish	Commercial fishing
Thunnus maccoyii	Southern bluefin tuna	Commercial fishing
Carcharhinus brachyurus	Bronze whaler	Commercial fishing
Carcharhinus longimanus	Oceanic whitetip shark	Commercial fishing

Sphyrna spp.	Hammerhead shark	Commercial fishing
Galeocerdo cuvier	Tiger shark	Commercial fishing
Carcharhinus falciformis	Silky shark	Commercial fishing
Sarda australis	Australian bonito	Commercial fishing
Carcharhinus limbatus	Dusky shark	Commercial fishing
Lamna nasus	Porbeagle	Commercial fishing
Alopias vulpinus	Thresher shark	Commercial fishing
Scomberomorus commerson	Narrow barred Spanish mackerel	Commercial fishing
Rachycentron canadum	Black kingfish	Commercial fishing
Isurus paucus	Longfin mako	Commercial fishing
Carcharodon carcharias	Great white shark	Bycatch
Elegatis bipinnulata	Rainbow runner	Bycatch
Pseudocarcharias kamoharai	Crocodile shark	Bycatch
Caranx igonbilis	Giant trevally	Bycatch
Alepisaurus ferox	Lancetfish	Bycatch
Manta birostris	Manta ray	Bycatch
Marine turtles	Various	Bycatch
Seabirds	Various	Bycatch