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REVIEW

Comparing bycatch mitigation strategies for vulnerable marine megafauna

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Abstract

Marine megafauna such as seabirds, marine mammals and sea turtles are subject to high mortality from incidental capture or bycatch in fisheries. Recent research suggests that fishing effort is increasing worldwide, highlighting the need to evaluate strategies intended to reduce marine megafauna bycatch. Here, we use three focal species (i.e. leatherback turtle *Dermochelys coriacea*, black-footed albatross *Phoebastria nigripes* and vaquita porpoise *Phocoena sinus*) as case studies to compare management outcomes of four bycatch mitigation measures: time–area closures, individual bycatch limits, gear modifications and buy-outs. Time–area closures were used for leatherbacks and vaquitas with limited effectiveness, although timing, size and enforcement influenced their efficacy. Individual bycatch limits were employed for leatherbacks in one fishery, sometimes simultaneously with gear modifications and closures. Gear modifications consistently reduced bycatch of leatherbacks and black-footed albatross and showed strong promise for vaquitas. True buy-outs were only used for vaquitas and were costly, most fishers were unwilling to be bought out, and it is unclear if they reduced bycatch. Our review suggests that gear modifications were the most widely used and generally most promising technique for these species, although management outcomes of each strategy depended largely on the species–fishery interaction, fishery characteristics and socioeconomic context. Based on lessons learned from our case studies, we outline when and where a particular approach may be most effective, provide recommendations for improving each strategy and highlight priorities for future research.

Introduction

Recent research has identified significant declines in fish stocks from global industrial fisheries, with at least half of all fisheries either fully exploited or overexploited (Worm *et al*., 2009; Branch *et al*., 2011; Ricard *et al*., 2012). Fishing effort has increased worldwide over the past few decades (Swartz *et al*., 2010; Anticamara *et al*., 2011), leading to concerns over the impacts on non-target animals and habitats (Lewison *et al*., 2004*a*, 2011). Marine megafauna such as seabirds, marine mammals and sea turtles are often subject to incidental mortality from fishing (Lewison *et al*., 2004*a*). Incidental capture of non-target species in fisheries, termed bycatch, is known or believed to cause declines in several marine megafauna populations worldwide (Lewison *et al*., 2004*a*; Peckham *et al*., 2007; Zydelis *et al*., 2009). These declines can have widespread ecological consequences, including extensive cascading effects on lower trophic levels (Estes *et al*., 2011).

Marine megafauna are particularly vulnerable to population-level impacts from bycatch due to their life-history characteristics (e.g. long life spans, late maturity, slow reproductive rates and wide-ranging movements) and propensity to interact with fisheries (Heppell *et al*., 2005; Peckham *et al*., 2007; Zydelis *et al*., 2009). Furthermore, many species frequently occur in close proximity to the coast (Block *et al*., 2011), and use nearshore habitats throughout their lives or during sensitive life stages (e.g. breeding/nursery areas, foraging hotspots and movement corridors). As human populations continue to rise, fishing effort is increasing in coastal areas worldwide (Stewart *et al*., 2010), highlighting the importance of evaluating strategies that seek to minimize interactions between marine megafauna and fisheries.

A review of bycatch species and management strategies can provide guidance for future planning and evaluation of mitigation efforts. Here, we use three focal species (i.e. leatherback turtle *Dermochelys coriacea*, black-footed albatross

Table 1 Status, life-history characteristics, bycatch impacts and current bycatch mitigation strategies of the three focal species; x indicates that the management strategy has been implemented or tested

Focal species	Current IUCN status	Distribution	Habitat use	Primary bycatch/fishery	Bycatch limits	Gear modifications	Time–area closures	Buy-outs
Leatherback turtle	Critically endangered	Global	Pelagic; coastal during breeding season	Longline, mesh net/industrial and small scale	x	x	x	x[a]
Black-footed albatross	Vulnerable	North Pacific	Pelagic; coastal during breeding season	Longline/industrial scale		x	x	
Vaquita porpoise	Critically endangered	Northern Gulf of California	Nearshore coastal	Mesh net, trawl/small scale		x[a]	x	x

[a]Testing of gear modification using a 'switch-out', which is a type of buy-out program that compensates fishers for using modified fishing gear. See text for further details.

Phoebastria nigripes and vaquita porpoise *Phocoena sinus*) as case studies to compare management outcomes of four bycatch mitigation strategies (i.e. time–area closures, individual bycatch limits, gear modifications and buy-outs). Due to inherent difficulties in evaluating mitigation methods across studies (Bull, 2007), our goal was to compare how the focal species responded to each management strategy by qualitatively synthesizing management outcomes from available published data. While our three focal species do not represent all marine megafauna–fisheries interactions, they provide detailed examples for each of the three major taxa groups that illustrate the range of issues we address. We selected the focal species because they are not targeted in fisheries, use pelagic and coastal habitats, occupy a broad range of positions in the food chain, are flagship species for conservation, encompass small and large distributions, and are jeopardized by bycatch in industrial and small-scale fisheries (Table 1). Based on lessons learned from these species, we highlight when and where a particular strategy would work best, provide recommendations for improving each technique and outline priorities for future research.

Focal species

Leatherback turtle

Life-history characteristics and current population status

Leatherback turtles *D. coriacea* are the largest, deepest diving and most migratory of all sea turtles, exhibiting the broadest geographic range of any living reptile (Eckert *et al*., 2012). They forage in temperate and subarctic waters worldwide and nest on tropical and subtropical beaches (Eckert *et al*., 2012). Leatherbacks are currently listed as critically endangered by the World Conservation Union (IUCN, 2012*a*). In the Pacific and Indo-Pacific, populations have declined precipitously and face extirpation within the next generation (Spotila *et al*., 2000), although smaller populations in the Atlantic appear to be increasing (TEWG, 2007; Stewart *et al*., 2011). The last published global population estimate suggested 34 500 nesting females (Spotila *et al*., 1996), although recent research estimated that the world's largest nesting population in West Africa had 15 730–41 373 females (Witt *et al*., 2009).

Fishery interactions and bycatch impacts

Incidental bycatch in fisheries represents a serious threat to leatherback populations worldwide (Lewison, Freeman & Crowder, 2004*b*; Lewison & Crowder, 2007; Eckert *et al*., 2012). In pelagic longline fisheries, leatherbacks are attracted to baited hooks and usually become entangled in the gear, but are also occasionally hooked in the mouth (Gilman *et al*., 2006; Read, 2007). The best estimate of direct mortality from being entangled or hooked in the mouth ranges from 4 to 27% (Lewison & Crowder, 2007). In passive fisheries such as mesh net and pot fisheries, leatherbacks become entangled (Gilman *et al*., 2010; Eckert *et al*., 2012), whereas they are captured in trawl fisheries (Cox *et al*., 2007). In the year 2000 alone, more than 50 000 leatherbacks were estimated to be hooked in Pacific pelagic longline fisheries (Lewison *et al*., 2004*b*), and large nesting populations in the Caribbean are jeopardized by persistent bycatch in mesh net fisheries (Eckert *et al*., 2012). Entanglement in mesh net fisheries may cause higher mortality than longlines (Lewison & Crowder, 2007), and leatherbacks frequently encounter these fisheries while inhabiting coastal waters during the breeding season (Eckert *et al*., 2012).

Black-footed albatross

Life-history characteristics and current population status

Black-footed albatross *P. nigripes* reach maturity in 8–10 years, live 40–50 years, mate for life and produce one chick per breeding season (Lewison & Crowder, 2003). Their range encompasses the North Pacific and *c*. 95% of the population nests in the Northwestern Hawaiian Islands (Arata, Sievert & Naughton, 2009). The species is currently listed as vulnerable by the World Conservation Union

(IUCN, 2012*b*), with the most recent population estimated at 129 000 individuals based on counts from the 2006–2007 breeding season (Flint, 2007). The species is expected to decline rapidly over the next three generations (2009–2065) if bycatch mitigation measures in longline fisheries are inadequate (IUCN, 2012*b*), although the current population is believed to be stable or slightly increasing (Arata *et al.*, 2009).

Fishery interactions and bycatch impacts

Black-footed albatross are taken as bycatch in pelagic and demersal longline fisheries throughout their range, as their foraging distribution frequently overlaps with these fisheries (Fischer *et al.*, 2009). Bycatch also occurs in driftnet fisheries (IUCN, 2012*b*), trawl fisheries (Fischer *et al.*, 2009), and possibly gillnet and troll fisheries (Lewison & Crowder, 2003). In longline fisheries, black-footed albatross are attracted to baited hooks when lines are deployed, and drown after they are hooked and pulled underwater (Lewison & Crowder, 2003). Bycatch in US, Japanese and Taiwanese pelagic longline fisheries may kill 5000–14 000 animals per year (Lewison & Crowder, 2003).

Vaquita porpoise

Life-history characteristics and current population status

The vaquita porpoise *P. sinus* is the world's smallest and most endangered cetacean (Rojas-Bracho, Reeves & Jaramillo-Legorreta, 2006; Jaramillo-Legorreta *et al.*, 2007). This critically endangered species (IUCN, 2012*c*) is endemic to shallow waters (< 40 m) in the northern Gulf of California and occupies the smallest known range of any cetacean (Rojas-Bracho *et al.*, 2006; IUCN, 2012*c*). Given their cryptic nature and naturally low abundance, little is known about vaquita life-history characteristics. The most current population estimates from 2007 ranged from 150 (Jaramillo-Legorreta *et al.*, 2007) to 226 individuals (Gerrodette & Rojas-Brancho, 2011), down from an estimated 500–600 individuals in the late 1990s (Jefferson, Webber & Pitman, 2008).

Fishery interactions and bycatch impacts

Vaquita are incidentally taken in mesh net and trawl fisheries throughout their range in the upper Gulf of California, where they drown after being entangled or captured. It is believed that vaquita started declining in the 1940s when large-mesh gillnet fisheries targeting totoaba *Totoaba macdonaldi* first became widespread in the Gulf (Rojas-Bracho *et al.*, 2006). Small-mesh gillnet and trawl fisheries targeting shrimp, elasmobranchs and finfish are now the greatest threat to vaquita following the collapse and closure of the totoaba fishery in the early 1980s (D'Agrosa, Lennert-Cody & Vidal, 2000; Rojas-Bracho *et al.*, 2006; Barlow *et al.*, 2010). The only known bycatch rate estimated that at least 39 individuals were taken per year from 1993 to 1995 in just one of three main fishing areas in their range (D'Agrosa *et al.*, 2000), and recent research suggests that vaquita bycatch needs to be eliminated in order to prevent their imminent extinction (Jaramillo-Legorreta *et al.*, 2007; Gerrodette & Rojas-Brancho, 2011).

Overview and synthesis of fishery management strategies

Time–area closures

Many marine megafauna form spatially and temporally predictable aggregations that become focal areas for both conservation and fisheries. Time–area closures are employed for marine megafauna to reduce bycatch or protect sensitive life stages (Grantham, Petersen & Possingham, 2008; Vanderlaan *et al.*, 2008; Game *et al.*, 2009; Armsworth *et al.*, 2010), and vary in jurisdiction, timing and size. Time–area closures may prohibit fishing, allow fishing only within specific areas or at specific times or permit fishing for non-target species. In general, time–area closures are easier to monitor and enforce within the Exclusive Economic Zones of the regulating nation; regulation in international waters is restricted to the fisheries of the regulating nation or international agreements (Leathwick *et al.*, 2008). Table 2 summarizes published data on time–area closures for each case study.

Leatherback turtle

Time–area closures have been employed in a few fisheries to mitigate leatherback bycatch. A time–area closure in the mid-1990s (a large area referred to as the 'Pacific leatherback conservation area') dramatically reduced bycatch in the Northeastern Pacific gillnet fishery (Moore *et al.*, 2009). However, a tagging study of leatherbacks in the North Atlantic found that relatively few animals utilized an area closed to US pelagic longliners to protect turtles, and most of the tagged animals traveled much farther distances to other non-protected areas of high pelagic longline use (James, Ottensmeyer & Myers, 2005). In addition, during a 4-year closure of the Hawaii longline swordfish fishery, leatherback bycatch was simply redistributed via other fisheries when imports from longline fleets (that replaced the Hawaii fleet) exhibited considerably higher ratios of leatherbacks to unit weight of swordfish (Gilman *et al.*, 2006).

Black-footed albatross and vaquita porpoise

Time–area closures have generally not been employed for black-footed albatrosses, likely because gear modifications are more popular among fishers, easier to implement both economically and socio-politically, and more likely to be voluntary or 'bottom-up'. In one published example, the closing of high-seas squid and salmon driftnet fisheries reduced the number of black-footed albatross killed annually (Naughton, Romano & Zimmerman, 2007). Time–area

Table 2 Synthesis of time–area closures for three focal marine megafauna species

Focal species	Fishery	Known reduction in bycatch	Summary of management outcome	References
Leatherback turtle	California/Oregon drift-net fishery	Yes	Bycatch reduced from a mean of 14 turtles killed per year to zero.	Moore *et al.* (2009)
Leatherback turtle	Hawaii longline swordfish fishery	No	Four-year closure redistributed bycatch to other fisheries.	Gilman *et al.* (2006)
Leatherback turtle	North Atlantic pelagic longline fishery	No	Tagged animals traveled to non-protected areas.	James *et al.* (2005)
Black-footed albatross	High-seas squid and salmon driftnet fisheries	Yes	Significantly reduced number of animals killed each year.	Naughton *et al.* (2007)
Vaquita porpoise	Northern Gulf of California small-scale gillnet fishery	No	70 and 63% population decline following closure (from 1993–2005).	Gerrodette & Rojas-Brancho (2011); Morzaria-Luna *et al.* (2012)
Vaquita porpoise	Northern Gulf of California small-scale gillnet fishery	No	25% population decline (from 2005 to 2008) after additional refuge area.	Gerrodette & Rojas-Brancho (2011)
Vaquita porpoise	Northern Gulf of California small-scale gillnet fishery	No	Estimated 8–99% probability of population increase from 2008 to 2018 based on three potential sizes of closure after PACE-Vaquita.	Gerrodette & Rojas-Brancho (2011); CIRVA (2012)

closures have been used over the past two decades to reduce vaquita bycatch. In 1993, the first Biosphere Reserve was established in the Northern Gulf of California and Colorado River Delta (Rojas-Bracho *et al.*, 2006), but populations declined 70% over the next 15 years (1993–2008) (Gerrodette & Rojas-Brancho, 2011). These declines appear to have continued even after a time–area closure specifically designed for vaquita was established in 2005, with an estimated population decline of 25% from 2005 to 2008 (Gerrodette & Rojas-Brancho, 2011). Although these closures have not produced measurable conservation outcomes, this appears to be a failure of implementation as the current spatial scale does not cover their entire range and enforcement has been inadequate (Gerrodette & Rojas-Brancho, 2011).

Individual bycatch limits

Individual bycatch limits cap the number of marine megafauna that a given fishery can remove as bycatch via observers or electronic surveillance on fishing vessels. Bycatch limits are usually determined by potential biological removals (PBRs) and biological opinions, and impose costs on a fishery for exceeding the cap (Holland, 2010). For example, the Hawaii longline swordfish fishery operates under annual bycatch limits for sea turtles, including turtles that are hooked, but released alive (Holland, 2010). Take limits for leatherbacks in this fishery are established using PBR-like and quasi-population viability approaches (Snover, 2008; Moore *et al.*, 2009).

Leatherbacks turtle

Individual bycatch limits exist for leatherbacks in some US commercial fisheries based on extrapolation of observed takes. Hawaii longline swordfish and tuna fisheries have employed individual bycatch limits on the number of leatherbacks taken annually. From 2004 to 2010, leatherback interactions in the Hawaii shallow-set longline fishery were below the 16-leatherback limit. However, in November of 2011, the fishery reached the 16-leatherback limit and was immediately closed for the remainder of the year (NOAA, 2012).

Black-footed albatross and vaquita porpoise

To our knowledge, individual bycatch limits have not been employed for black-footed albatrosses or vaquita porpoises. Bycatch limits have not been used for vaquita porpoises because an observer program would be difficult to implement in the small-scale Northern Gulf of California fisheries. Additionally, bycatch likely needs to be eliminated in order to prevent their extinction (Jaramillo-Legorreta *et al.*, 2007; Gerrodette & Rojas-Branch, 2011). Individual bycatch limits have not been employed for black-footed albatross because gear modifications are likely more popular with fishers and potentially more cost-effective.

Gear modifications

Gear modifications for marine megafauna include fishing gear designs that are less attractive or act as deterrents to non-target species, and mechanisms that allow escape or quick release of bycatch species (Hall, 1996; Wang, Fisler & Swimmer, 2010). Gear modifications are usually popular with fishers because they seek to avoid potentially more economically and politically costly decisions, and in some cases, fishers have advocated for them as a means to avoid fishery closures (Campbell & Cornwell, 2008). By keeping fishers fishing in desired locations and reducing bycatch, gear modifications present a potential 'win–win' scenario for fishers and fishery managers if adequately implemented (e.g. see Jenkins, 2007, 2010). Table 3 summarizes published data on gear modifications for the focal species.

Leatherback turtle

Gear modifications for leatherback turtles include circle hooks and bait/line modification for pelagic longline fisheries, Turtle Excluder Devices (TEDs) for trawl fisheries and net modifications for mesh net fisheries (Gilman *et al*., 2006, 2010). Circle hooks and bait changes have decreased bycatch in pelagic longline fisheries by 75%, 83%, 'significantly' (no percent reduction was given), 91% and 67% (Garrison, 2003; Watson *et al*., 2004; Gilman *et al*., 2007*a*; Pacheco *et al*., 2011; Santos *et al*., 2012), respectively. In all cases where circle hooks were combined with bait changes, reductions were observed when squid was replaced with mackerel or sardines (see Table 3). Observer data (Gilman *et al*., 2007*a*) and experiments (Watson *et al*., 2002) suggest that fewer leatherbacks were caught as bycatch on deeper branch lines. Similarly, lower profile nets in a gillnet fishery reduced leatherback bycatch by 32% and also increased catch rates of target species (Eckert *et al*., 2008). Regulations that increased the opening size of TEDs likely reduced annual leatherback mortality by 97% in US trawl fisheries (Epperly *et al*., 2002), and recent research suggests that gear modifications were largely responsible for reductions in leatherback bycatch and mortality between 1990 and 2007 (Finkbeiner *et al*., 2011). Two studies reported decreases in catch rates of some target species (Table 3).

Black-footed albatross

Gear modifications for reducing black-footed albatross in pelagic longline fisheries include tori lines (streamers that hang from a line attached at the stern of a fishing vessel), line-weighting, side-setting (setting longline gear from the side vs. the stern), bird curtains, night setting, setting in specific areas and bait-dyeing (Hyrenbach & Dotson, 2003; Gilman, Brothers & Kobayashi, 2007*b*). In three separate studies, blue-dyed bait reduced bycatch by 95, 94 and 63% (McNamara, Torre & Kaaialii, 1999; Boggs, 2001; Gilman *et al*., 2003*b*), respectively. Similarly, streamer lines reduced bycatch by 86% (McNamara *et al*., 1999) and contact rates with hooks by 76% (Boggs, 2001). Night setting decreased bycatch by 97% (McNamara *et al*., 1999), 93% (Boggs, 2001), 69% (Gilman, Kobayashi & Chaloupka, 2008), 98% (Boggs, 2001) and 98% (100% when combined with blue-dyed bait) (Boggs, 2003). Side-setting eliminated bycatch in two studies (Gilman *et al*., 2003*b*, 2007*a*) and also eliminated the need to move bait and gear between two work stations, increased deck space, did not foul gear in the propeller and carried no additional costs after the initial conversion (< \$1000) (Gilman *et al*., 2007*b*). The use of a 9-m underwater setting chute and 6.5-m underwater setting chute decreased combined black-footed-Laysan albatross bycatch rates by 38 and 88%, respectively (Gilman *et al*., 2003*b*). Weighted lines decreased contact rates with hooks by 92% (Boggs, 2001) and the use of a towed buoy and changes in offal discard practices mitigated bycatch by 86 and 88%, respectively (McNamara *et al*., 1999). In the Hawaii longline tuna fishery, multiple mandated gear modifications resulted in a 67% significant decrease in combined black-footed-Laysan albatross bycatch rates (Gilman *et al*., 2008). No studies reported decreases in catch rates or operational efficiency (Table 3).

Vaquita porpoise

Various gear modifications have been implemented under 'switch-outs' (see the Buy-outs section) to reduce vaquita bycatch (Avila-Forcada, Martínez-Cruz & Muñoz-Piña, 2012). The RS-INP shrimp trawl (developed by Mexico's National Fisheries Institute; INAPESCA) and Scorpion and Box trawl (developed by Southeast Fisheries Science Center) have been found to eliminate vaquita (and sea turtle) bycatch (Aguilar-Ramírez & Rodríquez-Valencia, 2010; CIRVA, 2012). Field trials have shown that the industrial version of the RS-INP trawl reduced bycatch-to-shrimp ratios between 20 and 50%, significantly reduced fish bycatch, consumed less fuel and caught more shrimp (CIRVA, 2012). Both the industrial and artisanal RS-INP design caught similar sizes of shrimp, with the artisanal version catching larger shrimp than traditional artisanal trawls. (CIRVA, 2012). The Mexican National Commission of Natural Protected Areas (CONANP) is currently encouraging and facilitating fishers to use hook and lines as well as fish traps instead of drift gillnets, while INAPESCA is testing the effectiveness of fish traps and trawls equipped with turtle excluder devices instead of gillnets (CIRVA, 2012; INAPESCA, pers. comm., 2013). No studies reported decreases in catch rates or operational efficiency (Table 3).

Buy-outs

A buy-out is a general term that can be used to describe the purchasing of fishers' vessels, permits or gear, or to compensate fishers for reducing fishing time or for switching gear types (Squires, 2010). Buy-outs have been used in a number of fisheries and try to overcome problems associated with overcapacity or overfishing (Holland, Gudmundsson & Gates, 1999). Fishery managers can either employ a buy-out, rent-out, switch-out or some combination (Avila-Forcada *et al*., 2012). A rent-out is an agreement by fishers to stop all fishing in a given area for a given amount of time, which can then be renewed; a switch-out compensates fishers for switching to a different gear type; and a true buy-out is when a fisher permanently turns in their fishing permits, boat and gear (Avila-Forcada *et al*., 2012).

Leatherback turtle and black-footed albatross

To our knowledge, buy-outs have not been used for black-footed albatross. Switch-outs have been employed to reduce leatherback (and loggerhead) bycatch in Ecuadorian

Table 3 Synthesis of gear modifications for three focal marine megafauna species

Focal species	Fishery	Known reduction in bycatch or contact rates	Known reduction in target catch rates or operational efficiency	Summary of management outcome	References
Leatherback turtle	Hawaii longline swordfish fishery	Yes	Target-species dependent	Circle hook and fish bait versus J hooks and squid bait significantly reduced bycatch rates by 83%, although success appears to depend on switching baits from squid to mackerel. Catch rates of some target species reduced.	Gilman *et al.* (2007*a*)
Leatherback turtle	Hawaii longline fisheries	Unknown	Unknown	Observer observations and line experiments showed more turtles hooked on shallowest branch lines.	Kleiber & Boggs (2000); Watson *et al.* (2002, 2005)
Leatherback turtle	US Atlantic pelagic longline swordfish fishery	Yes	Target-species dependent	From 2002 and 2003, circle hooks baited with squid reduced bycatch rates by 75% compared to J hooks baited with squid, while circle hooks baited with mackerel reduced bycatch rates by 67% compared to J hooks baited with mackerel. Catch rates of some target species increased or reduced.	Watson *et al.* (2004)
Leatherback turtle	Gulf of Mexico USA pelagic longline fishery	Yes	Unknown	Circle hooks baited with sardines during the day significantly reduced bycatch rates compared to J hooks baited with squid at night.	Garrison (2003)
Leatherback turtle	Trinidad surface gillnet mackerel fishery	Yes	No	Lower profile nets significantly reduced bycatch rates by 32%. Target catch rates increased.	Eckert *et al.* (2008)
Leatherback turtle	Gulf of Mexico and Southeast US shrimp trawl fisheries	Yes	Unknown	Increased opening size of TEDs estimated to reduce bycatch mortality by 97%.	Epperly *et al.* (2002)
Leatherback turtle	US fisheries	N/A	N/A	Gear modifications largely responsible for bycatch reductions from 1999 to 2007.	Finkbeiner *et al.* (2011)
Leatherback turtle	Portuguese swordfish pelagic longline fishery	Yes	Unknown	Circle hooks baited with mackerel reduced bycatch rates by 91% compared to J hooks baited with squid.	Santos *et al.* (2012)
Leatherback turtle	South Atlantic pelagic tuna longline fishery	No[a]	No	Circle hooks with the same bait significantly reduced bycatch composition by 67% compared to J hooks. Circle hooks significantly increased catch rates of primary target species (bigeye tuna).	Pacheco *et al.* (2011)
Black-footed albatross	US North Pacific swordfish and tuna pelagic longline fisheries	Unknown	Unknown	Weighted lines, line-setting, and blue-dyed bait likely reduced annual bycatch mortality.	Melvin *et al.* (2001)

Black-footed albatross	US North Pacific swordfish and tuna pelagic longline fisheries	Yes	No	Blue-dyed bait, a towed buoy, offal discards, streamer lines and night setting reduced bycatch rates by 95, 88, 86 and 97%, respectively. Blue-dyed bait increased target catch rates, while the others had no apparent effect.	McNamara *et al*. (1999)
Black-footed albatross	Hawaii longline swordfish fishery	Yes[b]	Unknown	Blue-dyed bait, streamer lines, and 60 g swivel weights 3.7 m above the bait reduced contact rates by 95, 75 and 93%, respectively.	Boggs (2001)
Black-footed albatross	Hawaii longline tuna fishery	Yes[b]	No	A 9-m underwater setting chute reduced combined black-footed-Laysan albatross contact rates by 95%. Based on bait retention, vessels would experience a gain in efficiency between 14.7 and 29.6%.	Gilman *et al*. (2003*a*)
Black-footed albatross	Hawaii longline swordfish fishery	Yes	N/A	Night setting and night setting + blue-dyed squid bait significantly reduced bycatch by 98 and 100%, respectively.	Boggs (2003)
Black-footed albatross	Hawaii longline tuna fishery	Yes	No	A 9-m underwater setting chute, 6.5-m underwater setting chute, blue-dyed bait, and side-setting reduced combined black-footed-Laysan albatross bycatch by 38, 88, 63 and 100%, respectively. Side-setting and blue-dyed bait did not significantly reduce setting time.	Gilman *et al*. (2003*b*)
Black-footed albatross	Hawaii longline tuna and swordfish fisheries	Yes	No	Side-setting eliminated bycatch. Side-setting eliminated the need to move gear and bait between two work stations, increasing available deck space.	Gilman *et al*. (2007*b*)
Black-footed albatross	Hawaii longline tuna fishery	Yes	No	Multiple mandated gear modifications resulted in a 67% significant decrease in black-footed-Laysan albatross bycatch rates. Weighted lines and side-setting presented several operational benefits.	Gilman *et al*. (2008)
[d]Vaquita porpoise	Northern Gulf of California gillnet fishery	Yes[c]	No	Modified trawl nets reportedly eliminated vaquita bycatch in trials. The industrial version reduced bycatch-to-shrimp ratios between 20 and 50%, significantly reduced fish bycatch, consumed less fuel and caught more shrimp, while the artisanal version caught larger shrimp and was more profitable.	Aguilar-Ramírez & Rodríquez-Valencia (2010); CIRVA (2012)
[d]Vaquita porpoise	Northern Gulf of California gillnet fishery	N/A	N/A	The Mexican National Commission of Natural Protected Areas is promoting the use of hook and line and traps instead of drift gillnets, which do not catch vaquita.	CIRVA (2012)
[d]Vaquita porpoise	Northern Gulf of California gillnet fishery	N/A	N/A	Mexico's National Fisheries Institute is testing the effectiveness of fish traps, which are believed to eliminate vaquita bycatch.	CIRVA (2012)

[a]Significant reduction in number of turtles caught using circle hooks (12 vs. 4), but no significant difference was found in bycatch rates due to small sample size.
[b]Bycatch expressed as contact rates does not necessarily result in birds being hooked or killed.
[c]Eliminated bycatch in trials, but given the rarity of vaquita bycatch events, it was impossible to compare bycatch rates.
[d]Gear modification implemented or currently being tested under a 'switch-out', which is a type of buy-out program that pays fishers to use modified fishing gear. See text for further details.
N/A, not applicable

surface longline fisheries. From 2004 to 2007, the World Wildlife Foundation, Inter-American Topical Tuna Commission and NOAA developed and implemented a circle hook exchange program where 330 569 J hooks were exchanged for circle hooks on 169 boats (Mug, Hall & Vogel, 2008). In the mahi-mahi fishery, circle hooks significantly reduced combined leatherback-loggerhead bycatch rates, but also significantly reduced target catch rates of mahi-mahi (Mug *et al*., 2008). In the tuna, billfish and shark fishery, circle hooks significantly reduced leatherback-loggerhead bycatch rates, with no effect on target catch rates. However, Mizrahi (2012) suggested that the use of circle hooks in this fishery may result in increased shark catches.

Vaquita porpoise

In 2008, the Mexican government issued a buy-out program that included buy-outs, switch-outs and rent-outs, and devoted almost $20 million to its implementation (Morell, 2008; Avila-Forcada *et al*., 2012). Fisher participation in the rent-out option was larger for fishers with savings and those who were members of cooperatives (Avila-Forcada *et al*., 2012). The switch-out option was chosen by fishers who owned their own boats, but participation decreased with the amount of profits per boat. True buy-outs attracted only older fishers who were planning to retire soon or fishers who possessed alternative skills, and became increasingly scarce as initial fishers set to retire were bought out (CIRVA, 2012). This is likely because fishers not set to retire wanted to continue fishing and may even benefit from less competition when other fishers are bought out (Gerrodette & Rojas-Brancho, 2011). The number of fishers entering the program has also changed since 2008, with 746, 324 and 683 fishers choosing one of the three options in 2008, 2009 and 2010, respectively (Avila-Forcada *et al*., 2012). The fishers that chose buy-outs and switch-outs (171 and 154) represent 8.2 and 7.4% of the estimated total fleet size in 2007, indicating that 15.6% of fishers have permanently switched to vaquita-safe fishing gear (Avila-Forcada *et al*., 2012). Furthermore, the buy-out has reportedly led to a 30% reduction in the number of gillnet vessels operating in the vaquita refuge in 2008 and 2009 (Gerrodette & Rojas-Brancho, 2011), although it is unknown if vaquita bycatch has decreased.

Lessons learned from focal species: when and where to implement a particular strategy?

Our case studies suggest that the success of each management strategy is largely dependent on the context of the fishery, species–fishery interaction and socioeconomic conditions (Gilman *et al*., 2006; Campbell & Cornwell, 2008). Potential costs and benefits will vary by location and bycatch species (Table 4). Thus, fisheries managers will need to identify biological issues and circumstances for each fishery–megafauna interaction, preferably working with fishers to determine the best course of action to minimize mortality while promoting sustainable fisheries.

Time–area closures versus other strategies

Time–area closures appeared to be of limited effectiveness for the focal species. Two of the three examples for leatherbacks reported that time–area closures were either the wrong size or re-distributed bycatch (Table 2). In these cases, gear modifications or bycatch limits likely would have been more effective than closures (Table 4). Similarly, closures for vaquitas were consistently too small and inadequately enforced (Gerrodette & Rojas-Brancho, 2011), suggesting that gear modifications may have been more effective if implemented in a top-down manner (see recommendations below; Table 4). Both black-footed albatross and leatherbacks were taken at high levels in Hawaii longline fisheries. In areas with many fisheries or in fisheries with multiple bycatch species, time–area closures may be preferable (Game *et al*., 2009; Lewison, Soykan & Franklin, 2009; Table 4).

Individual bycatch limits versus other strategies

Individual bycatch limits were rarely used as a bycatch mitigation tool for the focal species, likely because they require observers on most vessels to implement this technique. This is particularly difficult to enforce in small-scale fisheries and in countries that cannot afford observer programs (Lewison *et al*., 2004*a*). Although it is difficult to draw conclusions based on the focal species, we postulate that bycatch limits may be favored by fishers in cases where gear modifications result in decreased target catches or when closures move fishers into areas with lower target catches because bycatch limits avoid spatial redistribution of effort (if they apply to all fisheries) (Table 4). Another potential advantage of bycatch limits is that they do not require extensive field testing (assuming bycatch per vessel can be adequately estimated) (Table 4).

Gear modifications versus other strategies

Gear modifications were consistently successful at reducing bycatch of the focal species. However, in almost all cases, a single fishery was responsible for high bycatch, suggesting that gear modifications may be more effective in cases where a single fishery results in high bycatch (Lewison *et al*., 2009; Table 4). Gear modifications have the added benefit of not redistributing bycatch; in cases where there is a high risk of bycatch being redistributed in other fisheries following closures, buy-outs or closures resulting from bycatch limits being reached, gear modifications may be more effective over the other three strategies (Table 4). Additionally, in fisheries where target catches are not significantly reduced and fishers help develop the technology, gear modifications may have the added benefit of being favored by fishers

Table 4 Potential comparative advantages of four bycatch mitigation strategies for vulnerable marine megafauna. Advantage of strategy in column 1 is compared against strategies in columns 2–5

Management technique	Gear modifications	Time–area closures	Bycatch limits	Buy-outs
Gear modifications		• Keeps fishers fishing • May be more effective when bycatch is dispersed • May be more effective when a single fishery results in high bycatch • 'Bottom-up' approach may be more popular with fishers and easier to enforce • Unlikely to redistribute bycatch	• Will not result in closed fishery if limit exceeded • Potentially more expensive in short-term, but may be less costly in long-term because there is no need to pay observers • May avoid disincentives to reduce bycatch • 'Bottom-up' approach may be more popular with fishers and easier to enforce	• Keeps fishers fishing • Avoids potentially costly socioeconomic impacts • May be easier to implement • 'Bottom-up' approach may be more popular with fishers and easier to enforce • Unlikely to redistribute bycatch
Time–area closures	• May be more effective when bycatch is clustered • May be more effective where more than one species are taken as bycatch • May be more effective in areas with many high bycatch fisheries		• May be easier to implement if observer effort is unrealistic • May avoid disincentives to reduce bycatch	• Avoids potentially costly socioeconomic impacts • May be easier to implement • May be more popular with fishers • May be easier to enforce, especially over long time periods
Bycatch limits	• May be more popular with fishers in cases where gear modifications reduce target catch • Requires no field testing, which can be time intensive	• Keeps fishers fishing • Unlikely to redistribute bycatch • May be more effective when bycatch is dispersed		• Keeps fishers fishing • Avoids potentially costly socioeconomic impacts • May be easier to implement • May be more popular with fishers • May be easier to enforce, especially over long time periods
Buy-outs	• May be better in cases where immediate action is required • Fishers can be compensated	• May be better in cases where immediate action is required • Fishers can be compensated	• Fishers can be compensated, whereas this may not be the case if/when a bycatch limit results in a closed fishery	

(Table 4). Fishers may even be willing to accept a modest decrease in target catch if the modification allows them to fish in an area that would otherwise be closed (Read, 2007).

Buy-outs versus other strategies

True buy-outs were only used as a bycatch mitigation tool for our rarest species (i.e. vaquita). Although it is difficult to draw conclusions based on our focal species, we suggest that buy-outs are only an option in cases where immediate action is required and the socioeconomic consequences have been properly evaluated. In particular, they should only be considered over the other three strategies if a majority of fishers are willing to be bought out, if the buy-out will be adequately enforced, if fishers can find new jobs and if the buy-out can produce measurable bycatch reductions.

Management applications: recommendations for improving strategies

Fisheries managers will need to compare strategies through monitoring, evaluation and population modeling to ensure successful adaptive management. All management approaches should ideally be developed and implemented in a bottom-up approach, as fishers are much more likely to comply with mitigation measures that work well from an economic and operational standpoint, regardless of whether these measures are mandated or voluntary (Cox *et al.*, 2007). For example, fishers in the Hawaii longline tuna fishery voluntarily attached weights of 45 g or more within 1 m of the hook in 92% of sets at fishing grounds where seabird mitigation measures were not required (Gilman *et al.*, 2008). Additionally, more studies should report on follow-up implementations. Although a number of strategies we reviewed reduced bycatch, few studies reported on their long-term viability. Here, we outline recommendations for improving each strategy.

Bycatch limits can be improved by providing incentives for individual fishers to avoid bycatch since the limit is a common good shared by all fishers, which may actually create a disincentive for bycatch reduction whereby fishers try to optimize catch without trying to reduce bycatch because other vessels will simply reach the limit (Ning, Zhang & Fujita, 2009). Consequently, auctioning bycatch limits, also referred to as bycatch shares, may be one way to provide an incentive for bycatch mitigation by allowing vessels to transfer takes so that individual vessels are rewarded for reducing bycatch (Ning *et al.*, 2009). However, this will be difficult to achieve in fisheries where the number of individual animals that can be legally taken is far fewer than the number of vessels in the fishery (e.g. leatherback bycatch limits in Hawaii longline fisheries) (Holland, 2010).

Gear modifications appear to be more effective when treatment methods are combined (e.g. hook/line and bait changes), although this is highly dependent on a number of factors. Furthermore, although many gear modifications reduce bycatch in experimental trials, actual practice in fisheries is less effective (Cox *et al.*, 2007; Campbell & Cornwell, 2008). Thus, involving fishers in developing and testing gear modifications is critical for achieving fisher adoption of and compliance with gear modifications (Cox *et al.*, 2007; Jenkins, 2007, 2010; Lewison *et al.*, 2011). For example, the most widely adopted gear modifications in the US have been those developed by fishers (Jenkins, 2010). Gear modifications are also more likely to be adopted if they are developed locally, due in part to a 'local inventor effect' where familiarity with the inventor or his reputation may influence adopters' (Jenkins, 2007, 2010).

Buy-outs can be improved by better understanding the socioeconomic consequences of the type of buy-out chosen and how fishers will respond, the type of payment plan to be issued to fishers and how to prevent new vessels from entering a fishery after a buy-out (Squires, 2010). As demonstrated by our case study of vaquita, buy-outs will only work if fishers are willing to accept them. Furthermore, when integrating switch-outs with gear modifications, managers should consider compensating fisher's on a year-to-year basis for revenue losses if target catch rates decrease.

Research priorities: integrating demographic and socioeconomic models

Demographic models have helped inform fishery management by monitoring population trends and determining which life stages are most sensitive (Caswell, 2001). For example, Gerrodette & Rojas-Brancho (2011) and others (e.g. see Slooten, 2007; Slooten & Dawson, 2010) developed demographic models to assign different probabilities of population increases for various management schemes. In addition, bycatch assessment models that estimate management reference points (i.e. sustainable impact levels) may provide reasonable targets and ways to evaluate trade-offs of different management strategies, even when data are limited and highly uncertain (Moore *et al.*, in press). Future research should integrate demographic and bycatch assessment models with socioeconomic models, including fisher behavior, to develop predictive and decision-based models that compare potential outcomes of different management strategies (Hughes, Fenichel & Gerber, 2011; Fujitani *et al.*, 2012). All possible management techniques can be 'tested' to determine their potential efficacy while accounting for both biological and socioeconomic factors as parameters. In particular, models should carefully balance fisher behavior (e.g. whether or not fishers are willing to accept a particular management plan) with biological factors. For example, Morzaria-Luna *et al.* (2012) demonstrated that the best management plan for vaquita also led to a loss of income in fisheries that could not be recovered, while Hughes *et al.* (2011) incorporated fishery demographics with tourism, fishing effort and land use to examine the effects of different fishery management plans.

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