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Contribution to the Themed Section: 'Bycatch and discards: from improved knowledge to mitigation programmes'

Original Article

Evaluating effectiveness of time/area closures, quotas/caps, and fleet communications to reduce fisheries bycatch

Catherine E. O'Keefe*, Steven X. Cadrin, and Kevin D. E. Stokesbury

School for Marine Science and Technology, University of Massachusetts, 200 Mill Road, Suite 325, Fairhaven, MA 02719, USA

**Corresponding author: tel: +1 508 910 6340; fax +1 508 910 6374; e-mail: cokeefe@umassd.edu*

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Designing effective bycatch mitigation programmes requires an understanding of the life histories of target and non-target species, interactions of fish and fishing gear, effects of spatial and temporal shifts in fishing effort, socio-economic impacts to the fishery, and incentives of fishery participants. The effects of mitigation measures (including fishing gear modification, time/area closures, bycatch quotas and caps, incentive programs, and fleet communication programs) have been evaluated with respect to reducing bycatch and discards. Less attention has been focused on evaluating unanticipated results related to shifts in fishing effort, changes in the size of non-target species caught, reduced catch of target species, and economic viability to fishing fleets. Time/area closures, bycatch quotas/caps, and fleet communication programmes were evaluated against a set of criteria to assess overall effectiveness in reducing bycatch without causing unintended biological and socio-economic impacts. The results suggest that wide-ranging studies of species' life histories, potential changes in fleet behaviour, and individual incentives are important for developing and implementing mitigation programmes. Combining a suite of mitigation techniques has been successful in meeting biological and socio-economic fisheries goals. Additionally, collaborative programmes that utilize the skill sets of fishers, scientists, and managers have increased effectiveness in meeting bycatch reduction objectives.

Keywords: bycatch mitigation, caps/quotas, fleet communications, time/area closures.

Introduction

The conservation impacts associated with bycatch and discards of non-target species in commercial fisheries range from the depletion of overfished and endangered species to the loss of ecological diversity (Alverson *et al.*, 1994; Benaka and Dobrzynski, 2004; Kelleher, 2005). Fisheries scientists, managers, and industry members are challenged to determine strategies to mitigate the impacts of bycatch while maintaining sustainable commercial harvest levels. Methods to mitigate bycatch include gear modifications or bans, effort reductions, time/area closures, quota systems, bycatch caps or total allowable catches, bycatch levies (Wilcox and Donlan, 2007), incentive programmes, and fleet communications. Mitigating discards can be accomplished through regulations for full retention fisheries, increased at-sea monitoring, market-based incentives to utilize more bycatch species, and bycatch quota systems. In some situations, these approaches have been successful for conservation and socio-economic goals (Alverson, *et al.*, 1994; Hall *et al.*, 2000; Hall and Mainprize, 2005). However, these methods can also lead to unintended biological and socio-economic impacts, including shifts in fishing effort, changes in catch at size of non-target species, potential impacts on long-term sustainability of ecosystems, reduced catch of target species, increased operational costs, and increased administrative responsibility (Hall, 1995; Crowder and Murawski, 1998; Finkelstein *et al.*, 2008).

Bycatch reduction approaches that are focused on minimizing impacts on specific species or species groups often vary in design from measures that focus on specific sectors of commercial fisheries. Highly migratory species, such as sea turtles, seabirds, marine mammals, and pelagic fish species, are susceptible to incidental catch in a large number of fisheries using a variety of fishing gears

(Hall *et al.*, 2000; Tuck *et al.*, 2003; Lewison *et al.*, 2004; Read *et al.*, 2006; Anderson *et al.*, 2011). Minimizing the bycatch of these species, and the subsequent cumulative population impacts, often requires managing a number of fisheries simultaneously. Benthic species of fish, shellfish, and invertebrates that are limited to specific habitats may be more vulnerable to certain gear types or sectors of the fishery operating on discrete spatial scales (Alverson *et al.*, 1994). Mitigating bycatch under these circumstances more often focuses on explicit tactics within a single fishery or a fishery sector.

Designing effective bycatch mitigation programmes requires an understanding of life histories of target and non-target species, interactions of fish and fishing gear, effects of spatial and temporal shifts in fishing effort, socio-economic impacts to the fishery, and incentives of fishery participants. The primary objective of mitigation programmes to reduce bycatch may be unsuccessful if the effects of spatial or temporal shifts in fishing effort are not considered in programme design (Ashford *et al.*, 1995; Powell *et al.*, 2004; Powers and Abeare, 2009). Similarly, a programme designed to reduce the bycatch of a specific size range of a species (i.e. juveniles) could inadvertently create negative consequences within the larger ecosystem context (Hiddink *et al.*, 2008). Bycatch reduction devices and gear modifications may reduce bycatch that is brought onboard a vessel. However, it is important to consider the interactions of a modified gear with bycatch species in the water (Robertson and Chilvers, 2011). Bycatch reduction programmes that do not consider the economic viability to a fishing fleet or the incentives of the fishery participants are likely to create unintended socio-economic consequences (Crowder and Murawski, 1998).

Despite a growing global awareness of the negative effects of bycatch on population structure and marine environments, there have been few evaluations of the overall success of bycatch mitigation techniques, other than gear modifications. Potential bycatch solutions based on alternative fishing gears are typically tested for their effects on bycatch and target species, shifts in fishing effort, and economic viability using controlled field experiments. In contrast, effectiveness of time/area closures, bycatch quotas/caps, and fleet communications are not usually evaluated before implementation. Time/area closures have been employed as a bycatch reduction strategy for many species; however, the effectiveness of this technique in meeting bycatch reduction objectives has received little attention (Murray *et al.*, 2000). Bycatch quotas and caps have been applied to maintain the target population levels for decades, but continued declines in sea turtles, marine mammals, and depressed fish stocks suggest that the effectiveness of the technique may be limited because of confounding factors, such as misreporting, inappropriately set catch limits, or insufficient incentive systems (Abbott and Wilen, 2009). Fleet communication programmes have recently received increased attention as a possible solution for bycatch by incorporating fishery incentives, but programme reviews are scarce.

We evaluate bycatch mitigation programmes, focusing on the effectiveness of techniques in meeting objectives to reduce bycatch and discards without causing unintended impacts. Examples of time/area closures, bycatch quotas/caps, and fleet communication programmes are reviewed with respect to a set of evaluation criteria including: (1) reduced identified bycatch or discards; (2) no or minimal negative effect on the catch of target species; (3) no or minimal negative effect on the catch of other non-target species or sizes; (4) no or minimal spatial or temporal displacement of bycatch; and (5) economic viability for the fishery. The case studies represent a variety of fisheries from different regions providing a broad overview of mitigation techniques and have been peer-reviewed with respect to each of the evaluation criteria. We acknowledge that the case studies presented do not include the entire range of activity within each of the reviewed mitigation strategies, and results of our evaluation may not characterize all potential outcomes. Case studies of gear modifications to reduce bycatch have been extensively evaluated for a wide variety of species and fishing gear types (Alverson *et al.*, 1994; Glass, 2000; Hall *et al.*, 2000; Pol and Carr, 2000; Kennelly and Broadhurst, 2002; Valdemarsen and Suuronen, 2003; Catchpole and Gray, 2010), therefore were excluded from this review.

Methods

Results from each study were analysed to determine whether or not the programme met the five evaluation criteria. To meet criterion 1 (reduced identified bycatch or discards), the reviewed programme reported a statistically significant reduction in the bycatch species of interest after the mitigation programme was implemented compared with before. To meet criterion 2 (no or minimal negative effect on the catch of target species), the reviewed programme reported no change or an increase in the catch levels of targeted species. In some cases, results also indicated no significant change in the size composition of catch. Programmes met criterion 3 (no or minimal negative effect on the catch of other non-target species or sizes) when results indicated no significant change in catch levels or size composition for species that were not identified as targets or the bycatch species of interest. Criterion 4 (no or minimal spatial or temporal displacement of bycatch) evaluates the impacts of effort shifts in response to time/area closures and fleet communications and fishing restrictions resulting from bycatch quotas/caps. The criterion was met in programmes that reported no significant increases in the bycatch of the species of interest or other bycatch species in areas or times as a direct result of the implemented mitigation programme. To meet criterion 5 (economic viability for the fishery), the study considered the costs and benefits of the mitigation programme, and results indicated either no or minimal economic loss for the fishery from the programme or evidence that there were economic incentives from the fishery to implement the programme regardless of cost. Some studies did not report economic results for the fishery, and the economic viability of these programmes was not evaluated.

Evaluation

Time/area closures

Mitigating bycatch using time/area closures focuses on variations in the degree of spatial or temporal overlap between target and bycatch species (Murawski, 1994). Closures can produce simple and enforceable regulations, but may lead to unintended results. Determining the appropriate closure size or season is difficult and the resulting spatial or temporal scale of closures is often impractical (Adlerstein and Trumble, 1998; Slooten, 2007). Also, closures in international waters or in areas where minimal fisheries monitoring occurs pose compliance and enforcement challenges (Monteiro *et al.*, 2010). Interannual variation in the spatial distribution of target and non-target species may cause a mismatch between management areas and high bycatch (Goldsworthy and Page, 2007; Grantham *et al.*, 2008; Witt *et al.*, 2008). Closures may relocate the bycatch problem either spatially or temporally (Powers and Abeare, 2009; Diamond *et al.*, 2010) or create unbalanced levels of exploitation (Walters, 2000). They can also lead to socio-economic impacts from increased steaming times to new areas and associated fuel costs, lost fishing opportunities, reduced catch of target species, or disproportionate effects on specific factions of a fishing fleet (Murray *et al.*, 2000; Harley and Suter, 2007; Armsworth *et al.*, 2010). Examples of time/area closures are evaluated to demonstrate aspects that are effective to reduce bycatch and aspects that can cause unintended results.

Shrimp trawling in tropical waters can produce a 10:1 bycatch to shrimp ratio when executed without bycatch reduction measures. Ye *et al.* (2000) characterized the bycatch to shrimp ratio in the Kuwait shrimp fishery and found seasonal patterns of bycatch to shrimp ratios in inshore vs. offshore waters. They also experimentally compared the non-target species to shrimp catch ratios inside and outside of closed areas using data from a year-round shrimp survey. Areas of Kuwait Bay and within the three mile Exclusive Economic Zone along the coast were closed to shrimp trawling in 1983 (Ye *et al.*, 2000). The comparison of survey catch inside and outside of the closures showed reductions in the non-target species to shrimp ratio in the closure areas, with no difference in the catch rate of shrimp. The study strongly supports the conclusion that the closures effectively reduced bycatch in shrimp trawling, without impacting shrimp catches within the entire Kuwait shrimp fishery. The study also indicates that the spatial and temporal variability in bycatch to shrimp ratios should be predetermined to assist in identifying times and areas for closures to reduce bycatch. Our evaluation of the reported results suggests that the programme met criteria 1 through 4. Bycatch of non-target species was significantly reduced, there were no reported negative impacts on the catch levels of shrimp, and there were no negative impacts on the catch of other non-targeted species. The study did not report on impacts of effort shifts resulting from the area closures, or on the economic viability of the programme. However, reported bycatch levels suggest that minimal spatial and temporal displacement of bycatch occurred as a result of the closure outside the closed region before and after implementation. Despite the effectiveness of the Kuwait area closures, the bycatch problem has persisted in the shrimp fishery. A deteriorated fishery management system with lack of funding for monitoring and enforcement has resulted in illegal fishing within the closed areas and impacts on bycatch species (De Young, 2006).

The use of time/area closures failed to reduce the bycatch of harbour porpoises with minimal impacts on the fishing practices of the sink gillnet fishery in the Gulf of Maine (Murray *et al.*, 2000). The high bycatch of harbour porpoises prompted managers to close three regions of the Gulf of Maine in 1994 based on historically high bycatch rates and considerable data on fishing effort. The areas were not effective in reducing bycatch because of the spatial and temporal variation in patterns of the bycatch rate and the displacement of bycatch events to areas outside of the closures. The closure areas focused on the regions that had been historically fished, without considering bycatch events that could occur as a result of effort displacement to areas outside of the closures. Results from Murray *et al.* (2000) suggest that a larger closure may have reduced bycatch and curbed the impacts on the harbour porpoise population from effort displacement, but may have significantly impaired fishery operations. Placement of the closures had disproportionate effects on the fishing communities of New Hampshire, and Murray *et al.* (2000) state that it is unlikely that small time/area closures can be placed in a manner to meet the requirements of National Standard 4 of the Magnuson-Stevens Act. National Standard 4 states that "conservation and management measures shall not discriminate between residents of different states" (USDOC, 2007). Furthermore, the expected bycatch of harbour porpoises can be over or underestimated if fishing effort shifts are not considered in the determination of the closure area or time or if there are insufficient data on the variable patterns of target and bycatch species distribution. Our evaluation of the study suggests that the harbour porpoise closures met criterion 3 because no negative effects on the catch of other non-target species were reported. The closures did not meet any of the other evaluation criteria. Subsequently, the areas were expanded spatially and temporally to reflect the interannual variability in harbour porpoise migration patterns, and "pingers", sound-producing porpoise deterrents, were required on gillnets to prevent porpoises from interacting with the gear (USDOC, 1998). The large spatial and temporal extent of the closures has prompted research on alternative mitigation strategies, including individual bycatch quotas (Bisack and Sutinen, 2006) and "consequence" closures, which prohibit fishing activity in large regions if target bycatch rates are exceeded in two consecutive management seasons (USDOC, 2010).

The "plaice box" was introduced in the North Sea in 1989 with a goal of reducing discarding of undersized plaice in the beam and otter trawl fisheries (Pastoors *et al.*, 2000). The box was initially implemented as a quarterly closure, but extended to a year-round closure in 1995 for vessels larger than 300 horsepower. The rationale for the closure was that reduced fishing effort in the area where the highest juvenile plaice discarding occurred would reduce overall discarding. Although compliance was high, and discarding was reduced, the overall survival of juvenile plaice in the area did not increase. A slower growth rate of prerecruits was observed inside the plaice box when compared with outside. Pastoors *et al.* (2000) hypothesized that the observed slower growth rate of juvenile plaice resulted from density-dependent factors of increased predation and lower food availability, causing increased natural mortality. They inferred an interaction between bottom trawling activities, food availability, and spatial distribution of plaice. Excluding bottom trawling from the plaice box may have adversely affected benthic food assemblage and availability and, therefore, offset the positive effects of reduced discarding. Pastoors *et al.* (2000) suggest that a protected area alone may be counter-productive to increasing the survival of juvenile plaice and that further study on a combination of discard mitigation measures is warranted. The plaice box closure met criterion 1, reduced identified bycatch or discards. However, criteria 2 and 4 were not met: decreased survivability of juvenile plaice impacted the catch of adult plaice in the long term, and there has been a reported increase in the abundance of juvenile plaice in waters outside of the closure leading to an increase in bycatch and discards in these regions (Hiddink *et al.*, 2008). The study did not report effects on the catch of other non-target species or consider the economic viability of the closure.

Substantial scup discards in the Mid-Atlantic Bight prompted the Mid-Atlantic Fisheries Management Council to implement area closures, termed gear-restricted areas, for the *Loligo* squid fishery in 2000 based on historical discard data from the small-mesh fisheries in the Mid-Atlantic (Powell *et al.*, 2004). The effectiveness of the gear restricted areas was not evaluated after implementation because no fishing was allowed in the regions. In addition to the area closures, which significantly impaired the *Loligo* fishery, a modified squid net was designed to potentially allow escapement of scup and other bycatch species (Powell *et al.*, 2004). Powell *et al.* (2004) tested the effectiveness of the gear modifications inside the gear restricted areas, providing the first evaluation of the closures. The experimental results suggest that the area closures increased overall discarding of scup in the *Loligo* fishery due to higher bycatch rates outside of the closed areas than inside. The gear restricted areas restricted fishing in areas with high catch per unit effort of target species and low bycatch rates. The squid fishery accounted for ~7% of scup discards, and the gear restricted areas may have been more appropriate for the small-mesh fishery targeting butterfish (19% of scup discards) or adult scup (56% of scup discards; Powell *et al.*, 2004). Additionally, there were increased rates of discards of other non-targeted species, possibly due to fleet redeployment. The modified gear did allow scup escapement and reduced scup discarding; however, there was a significant loss of target species catch. The study concluded that fishers would likely increase effort to obtain the desired *Loligo* catch, which would negate any positive effects of the restricted areas and gear modifications on scup discarding. Powell *et al.* (2004) suggest that a change in minimum landing size would likely remedy the scup discarding problem in the *Loligo* fishery. The closures did not meet any of the evaluation criteria. Current regulations allow the *Loligo* fishery to operate in the restricted areas with specific gear configurations (USDOC, 2012), and recent research has focused on the real-time avoidance of bycatch hotspots based on oceanographic and environmental conditions (Kohut and Manderson, 2012).

Bycatch of the New Zealand sea lion in the arrow squid trawl fishery has been cited as a possible cause for population decline (Chilvers, 2008). New Zealand sea lions' breeding grounds are spatially limited to small regions of Subantarctic islands surrounded by a no-take Marine Reserve area, which prohibits all fishing activities extending to 22 km offshore. Despite the area-based protection, pup production declined significantly since the early 2000s (Chilvers, 2008). The squid fishery is one of the largest commercial fisheries in New Zealand with exports comprising over 10% of the total New Zealand export value. Approximately 25% of the squid catch is taken from areas just outside of the Marine Reserve off of Campbell Island. Chilvers (2008) analysed the biology and foraging ecology of New Zealand sea lions and suggested that the current closure areas do not meet bycatch reduction objectives. The areas do not encompass the entire foraging range of lactating females, which has resulted in bycatch of females outside of the Marine Reserve and an increased likelihood of death of orphaned pups. Additional mitigation measures, including a bycatch cap with in-season fishery closure and gear modifications, have not been successful in reducing the population decline (Diamond, 2004). Chilvers (2008) suggests that increasing the closure area to include all the sea lion foraging grounds may result in bycatch reduction by the trawl fleet and aid in increasing the sea lion population size. However, the magnitude of such a closure would reduce the available fishing grounds by more than 50% and likely result in negative economic impacts. Our evaluation of the Marine Reserve suggests that this mitigation programme does not meet criterion 1 to reduce intended bycatch. Increasing the size of the closure would likely result in a programme that would not meet criteria 2, 4, and 5. According to researchers at New Zealand's University of Otago, the number of sea lion takes has likely increased since 2008 due to the lack of strong enforcement of the bycatch cap and misreporting of catch. The area-based bycatch mitigation plan has not been revised and the sea lion population continues to decline.

Effectiveness of time/area closures for reducing bycatch and discards has not been extensively investigated because fishing effort is typically prohibited once the areas are closed. There is evidence that overall bycatch rates within management regions or specific fisheries have decreased in response to closures for some species, e.g. rockfish in the eastern Pacific (Dalton and Ralston, 2004), demersal fish in the North Sea (Catchpole *et al.*, 2005), albatross in the Southern Ocean (Croxall, 2008), and Australian gulper sharks (White and Kyne, 2010). Efforts to model the effects of closures have become more prevalent in recent literature (Adlerstein and Trumble, 1998; Hobday and Hartmann, 2006; Grantham *et al.*, 2008; Powers and Abeare, 2009; Diamond *et al.*, 2010) and can be informative for management decisions on size, location, and duration of closures to meet bycatch reduction objectives. Additionally, there is a large body of literature on the effectiveness of closed areas and marine protected areas as a tool for fisheries management (Cadrin *et al.*, 1995; Gubbay, 1995; Murawski *et al.*, 2000; Edgar *et al.*, 2007).

Time/area closures can be effective for reducing bycatch and discards, as experienced in the Kuwait shrimp fishery. However, as demonstrated by the examples of harbour porpoise in the Gulf of Maine, juvenile plaice in the North Sea, and sea lions in New Zealand, unintended ecological results can occur from closures that do not account for the life-history characteristics of the target and non-target species. Unintended socio-economic results can also occur when distributional impacts are not considered in implementation as described in the Gulf of Maine porpoise closure and Mid-Atlantic scup gear restricted areas. Time/area closures are also less popular among fishers, because they are viewed as "fencing off the ocean". This passive mitigation technique, where the fishing industry is forced to move out of certain fishing grounds, is often viewed as an incentive for more active mitigation methods, such as gear modifications or fleet communications. Used in combination with other mitigation techniques, time/area closures may be more effective for reducing bycatch and discards than when used alone.

Bycatch quotas/caps

Bycatch can be limited through the use of quotas, caps, and total allowable catches. Quotas and caps can be applied individually or fleet-wide, allow for transfer or purchase, and can be designed to manage both target and non-target species (Alverson *et al.*, 1994). Bycatch caps are typically administered on a fleet-wide basis to control protected species, such as seabirds (Dillingham and Fletcher, 2008), mammals (Wade, 1998), or turtles (Finkbeiner *et al.*, 2011), or to control the bycatch of depleted fish stocks in mixed species fisheries (Murawski, 1991). Quotas are most often applied individually and include provisions for purchase or lease. These types of bycatch mitigation programmes rely on high levels of at-sea observer coverage and are most effective when incentives and disincentives are clear and enforceable (Diamond, 2004). Although bycatch can be controlled through quotas and caps, economic impacts resulting from lost fishing opportunities or increased operating costs can be severe (Holland, 2010). Case studies were evaluated to demonstrate a range of results related to reduced bycatch and discards through the use of bycatch quotas and caps.

The US sea scallop fishery employed a bycatch cap for yellowtail flounder in specific regions of Georges Bank starting in 1999. The fishery was spatially limited to protect important juvenile groundfish habitat and temporally restricted to avoid spawning times for groundfish (NEFMC, 1999). Additionally, a specific measure to limit the bycatch of yellowtail flounder in the scallop fishery was incorporated in the management plan. The yellowtail flounder allocation to the scallop fleet was initially limited to 10% of the total allowable catch of yellowtail flounder to promote rebuilding plans (NEFMC, 2000). The 10% allocation cap was applied to the entire scallop fleet, without individual accountability, which created derby-style fishing to avoid the individual loss of scallop yield. Reaching the bycatch cap closed the scallop fishery in certain areas before the full scallop allocation was taken several times between 1999 and 2009 (O'Keefe *et al.*, 2010). Early closure resulted in foregone scallop yield, concern about scallop health and natural mortality (Stokesbury *et al.*, 2007) and large economic losses. Foregone revenue resulting from the closures totalled over US $65 million between 2004 and 2009 (O'Keefe *et al.*, 2010). Additionally, closing specific areas to scallop fishing shifted effort to regions with lower catch per unit effort of the target species and higher bycatch of yellowtail flounder and other non-target species. Our evaluation of the results of the yellowtail flounder bycatch cap suggests that the programme met none of the evaluation criteria. Although bycatch was capped in certain areas causing in-season fishery closures, the resulting effort shifts increased bycatch in other areas. There were impacts on the catch of the target species by shifting effort out of high catch per unit effort regions, and an unquantified increase in the bycatch of other non-target species in addition to the negative economic consequences. The severe economic impacts incentivized the scallop fishery to collaborate with scientific partners in 2010 to develop a real-time bycatch avoidance system based on e-mail communications of yellowtail flounder bycatch hotspots (O'Keefe *et al.*, 2010). The bycatch avoidance system has aided the scallop fishery harvest the full allocation of scallops since 2010 without exceeding yellowtail flounder bycatch caps. However, the spatial scope of the avoidance programme does not encompass all regions where yellowtail bycatch occurs, and the scallop fishery continues to have high bycatch of yellowtail flounder throughout portions of the resource.

The British Columbia groundfish trawl fishery instituted a bycatch quota in 1996 to reduce the incidental catch and subsequent mortality of Pacific halibut. By 1995, the management system of trip limits and fleet wide total allowable catches of halibut that had been in place since the 1970s proved insufficient to prevent an overage of bycatch, resulting in a total fishery closure (Branch *et al.*, 2006). In 1996, Canada implemented an individual vessel bycatch quota option for the trawl fleet in an effort to reduce halibut bycatch through individual accountability. Vessels could opt to participate in the bycatch quota programme, requiring them to pay for 100% at-sea observer coverage. The individual vessel bycatch quota was set by dividing the fleet bycatch quota among the participating vessels and the monitoring quota in each trimester. When a vessel reached their quota within a trimester, they could not fish until the start of the next trimester. There was a near fivefold reduction in halibut bycatch under the individual vessel bycatch quota system between 1995 and 1996 (Diamond, 2004). In 1997, the system transformed to an individual vessel quota system with annual catch limits for all managed species. Halibut was allocated as a ratio to each vessel holding quota for any of the managed groundfish species (i.e. if a vessel held 1% of the groundfish quota, it would receive 1% of the halibut bycatch total allowable catch; Ackerman and Turris, 2012). Halibut remained a prohibited species and the quota was transferable between vessels. If a vessel reached their halibut quota, they were restricted to the midwater trawl gear until the end of the fishing year or until they could acquire more halibut quota. The programme resulted in a significant reduction in halibut bycatch mortality with the groundfish fleet reaching an average of 31% of the halibut total allowable catch in the last 15 years (Ackerman and Turris, 2012). The individual quota programme meets criteria 1 through 4. Economic analyses of the programme have reported varying results (Diamond, 2004; Pinkerton and Edwards, 2009; Turris, 2010; Grimm *et al.*, 2012). High levels of observer coverage increase operational costs to the fishery, and quota transferability incurs costs that may not be viable for small business operations leading to fleet consolidation. Conversely, the increased utilization of healthy target stocks can increase profits, and extending the fishing season by removing the "race to fish" can create increased market opportunities. Due to these contrasting views on the economic viability of the individual quota system, we did not make a determination of whether or not the programme meets criterion 5.

The New Zealand Quota Management System implemented in 2001 resulted in reduced discards of managed species through individual catch limits (Diamond, 2004). The system was originally designed in 1986 with requirements to have individual quotas for all managed species or have any non-managed species listed on fishing permits. However, a loophole allowed bycatch of species for which no quota was held if it was caught in a mixed species fishery. This loophole resulted in exceeding catch limits for many managed species and encouraged targeting of non-managed species (Diamond, 2004). Additionally, fishers were allowed to trade the quota of one species for another, according to specified ratios, to account for bycatch. This transferability system made it difficult to establish and enforce total allowable catches, and impossible to control the total amount of fish caught within each species (Lock and Leslie, 2007). Under the 2001 Quota Management System revision, the bycatch loophole was removed, and a catch balancing system was enhanced to incorporate fees, called deemed values, or purchase of quota to account for bycatch. If vessels did not account for their full catch, the fishing permit was suspended. The more stringent regulations made bycatch costly to the fishing industry and resulted in reduced bycatch and increased targeting of healthy stocks (Diamond, 2004; Lock and Leslie, 2007). The quota system was effective in reducing bycatch because of several criteria, including 100% observer coverage, small fleet size, limited landing ports, reliable enforcement, and strong penalties for non-compliance. Meeting all these criteria was critical to the success in New Zealand, but would likely be difficult to meet in other fisheries (Diamond, 2004). This system meets evaluation criteria 1, 2, and 4, because several modifications to directly address bycatch have been integrated in the plan over time, and the programme has considered the impacts of quotas on the catch of target species and potential shifts in fishing effort. The system does not meet criterion 3 because the catch balancing policy shifted targeting to a variety of species over time, often resulting in over- or underfishing specific stocks. The Quota Management System has been revised and enhanced several times since 1986 with a primary objective to maintain economic viability for the fishing industry. Although there have been shortfalls in meeting this objective for all factions of the fleet, the system meets criterion 5 due to the variety of available options to maintain cost-effective bycatch mitigation.

Reducing bycatch and discards through the use of quotas or caps can be effective for fisheries with strong economic incentives and disincentives. Early fishery closures cause economic loss of unharvested target species, as demonstrated in the sea scallop example. The high costs of early closures provide an incentive to fishing fleets to stay within total allowable catches, effectively maintaining bycatch targets. However, in-season caps can cause similar unintended results as time/area closures, e.g. shifting fishing effort to areas of high bycatch or reduced target species catch, and disproportionately impacting factions of the fishing fleet. In-season caps that allow fishing fleets to move to different fishing areas or to carry-over allocations of target species to subsequent years may be effective in reducing economic impacts. Quota systems can incentivize fishery participants to reduce bycatch through individual accountability. The likelihood of exceeding bycatch quotas is reduced when the penalties for individual vessels render the business non-competitive (Annala, 1996; Diamond, 2004; Turris, 2010). Quotas and caps are not effective if bycatch events are rare or unpredictable (Diamond, 2004). In situations where the distributional overlap of target and non-target species is not well-understood or trading schemes allow the transfer of one species for another, bycatch caps and quotas can be set too high or too low (Lock and Leslie, 2007; Abbott and Wilen, 2010). Combining bycatch quotas or caps with gear modifications or fleet communication programmes may reduce negative economic impacts, as documented in the international tuna-dolphin debate (Coe *et al.*, 1984; Hall, 1998; Hannesson, 2008). Furthermore, combining individual bycatch quotas with time/area closures may reduce the negative consequences of area-based management alone (Waugh *et al.*, 2008). Allowing for the transferability of the bycatch quota between individual fishing entities could facilitate the optimal harvest of target species while maintaining fleet-wide bycatch allocation limits (Branch *et al.*, 2006).

Fleet communication

Fleet communication programmes can be effective for reducing bycatch by facilitating avoidance with cooperating fishing vessels. Fleet communication is a voluntary form of time/area fishing patterns to reduce bycatch and has the potential to allow commercial fisheries to operate in a coordinated manner (Gilman *et al.*, 2006). Although this type of bycatch mitigation measure can be successful without causing unintended impacts, it relies on participation from the majority of fishing vessels and typically requires strong economic incentives. Examples are evaluated to demonstrate how fleet communication programmes develop through incentives and what aspects can be effective in reducing bycatch and discards.

The Sea State programme (Sea State Inc., Seattle, WA, USA) was designed to reduce unintended bycatch in mixed species fisheries in Alaska (Gauvin *et al.*, 1995). The goal of the programme was to use the bycatch rate information from all participants in a fishery to avoid areas with high bycatch. Data were collected from vessels in a real-time manner through satellite communications and conveyed to a third-party organization that analysed bycatch rates. The programme examined the relationship between bycatch rate and location and relayed information on bycatch hotspots back to the active fishing vessels in near real time. Success of the programme depended on participation from the fishery and peer pressure between vessels. The programme was successful in aiding the rock sole fishery to avoid crab bycatch by moving from areas with high bycatch rates to areas with lower rates of crab bycatch. While voluntary participation in the programme led to bycatch avoidance in some fisheries, lack of participation by individuals, or companies reduced the positive outcomes of the programme in other fisheries. In the yellowfin sole fishery, one quarter of the vessels did not participate and had high bycatch rates that forced an early end to the fishing season for the entire fleet (Gauvin *et al.*, 1995). Additionally, the programme was not successful in aiding the trawl fisheries avoid the bycatch of Chinook salmon due to the lack of a time/area relationship between target and bycatch species (Gauvin *et al.*, 1995). Effectiveness of the programme in meeting bycatch reduction objectives, while minimizing unintended consequences, results from a focus on the combined importance of institutional, economic, and natural criteria to form industry incentives (Abbott and Wilen, 2010). The programme reportedly saved the participating fleets millions of dollars (US) due to extending fishing seasons that were historically closed due to bycatch (Gilman *et al.*, 2006). Additionally, the formal and informal agreements between the fishing fleets and Sea State Inc. have reduced management costs and regulatory requirements (Gilman *et al.*, 2006). Since the initial implementation of the avoidance programme by Sea State in 1995, the company has expanded to include several fisheries and bycatch species from the US northwest Pacific region. The avoidance programmes have been integrated into fishery management plans allowing Sea State to designate fishery closure areas on a real-time basis (K. Haflinger, pers. comm.). Our evaluation of the reported results of the Sea State communications programme indicate that criteria 1 through 5 were met for fisheries where target and non-target species had a spatial or temporal relationship and when there were high levels of participation. Applying the avoidance programme to fisheries that lack a predictable overlap of target and non-target species or have less industry participation would not be effective in meeting criterion 1 (reduced identified bycatch or discards) or 5 (economic viability for the fishery).

Loggerhead turtle bycatch in the Hawaii-based pelagic longline fishery results from an overlap in productive fishing grounds and migrating turtles in the first quarter of the year at depths less than 100 m. Time/area closures, effort reductions, limited fishing permits, gear modifications, and increased fishery monitoring have all been employed to try to reduce the bycatch of loggerheads with mixed success since the mid-1990s (Howell *et al.*, 2008). After an early fishery closure in 2006, the Pacific Islands Fishery Science Center released "TurtleWatch" to assist in fishery and management decision-making. TurtleWatch utilized fishery-dependent data in combination with environmental data to predict the location of thermal bands where turtles may aggregate. The first TurtleWatch information was available for the first quarter of the 2007 fishing year; however, the fishery did not follow the advice for avoiding specific regions to reduce turtle bycatch. Turtle takes were observed in the advisory area, indicating that the avoidance information was accurate. Howell *et al.* (2008) conclude that the fishery utilization of the information was low and therefore bycatch objectives were not reached. However, Howell *et al.* (2008) suggest that with increased participation, the TurtleWatch tool could be a beneficial alternative to time/area closures or in-season bycatch caps. The bycatch of loggerheads was significantly reduced, with no takes in 2008 and three takes in 2009 (WPRFMC, 2011), while TurtleWatch provided updated advisories of potential turtle interaction zones. However, bycatch sharply increased in 2011, with 75% of the interactions occurring in the advisory region (WPRFMC, 2011). The TurtleWatch tool did not consistently meet criterion 1 (reduced identified bycatch or discards) because of low fishery participation. The programme would meet criteria 2, 3, and 4 if utilized because the avoidance regions were small compared with the fishing grounds, allowing the maintenance of target species catch levels and minimizing negative effects from shifts in effort. The programme did not meet criterion 5 as the economic incentives to participate were weak.

The North Pacific Longline Association voluntarily contracted a third-party company, Fisheries Information Services, to assist in halibut and seabird bycatch avoidance for the Alaska pelagic longline fishery starting in 1992 (Gilman *et al.*, 2006). The programme utilized transmitted observer data to inform the fleet about number and weight of hooked target and bycatch species, locations of gear deployment and retrieval, and fishing effort via e-mail. The information was also relayed to fleet owners and managers who could track individual vessel performance and apply consequential individual "enforcement" measures. During the first 4 years of the programme, fleet participation doubled from 14 to 28 vessels, and by 1999 included all active fishing vessels in the pelagic longline fleet (annual number of permitted vessels ranged from 64 to 74). The fleet was able to successfully target Pacific cod, Greenland turbot, and sablefish while reducing halibut bycatch up to 30% and seabird bycatch by ~20% (Gilman *et al.*, 2006). The fleet communication system was implemented simultaneously with other bycatch mitigation measures, including "careful release" practices for halibut and gear modifications for seabirds, which prevents a determination of the effect of the communication programme alone. However, halibut bycatch was greater in boats that incorporated gear modifications but did not participate in the communication programme, and seabird bycatch rates have decreased since the implementation of the communication programme resulting from vessel captains' awareness of the bycatch issue. The combined mitigation measures are still in place, the fishery has not closed early due to bycatch since 2001 (Gilman *et al.*, 2006), and halibut discard mortality rates have been reduced by 50% according to the Alaskan Pollock Freezer Longline Conservation Cooperative. Operating costs for the programme were reported at US $60 per observed vessel per week with an average daily value of the fishery estimated at US $350 000. Reported results of the fleet communications programme meet criteria 1 through 5. Due to the longevity of the programme, bycatch reduction objectives have been met while minimizing the negative effects of effort shifts and bycatch displacement and maintaining economic viability.

Proposed area closures to reduce bycatch of alosine species (American shad, alewife, and blueback herring) in the US Northwest Atlantic herring and mackerel trawl fisheries prompted the development of a voluntary avoidance system based on the fleet communication of at-sea and port-side observations (Bethoney *et al.*, 2013). The programme utilized a coded grid with discrete spatial units to identify high, moderate, and low bycatch regions, modelled after similar bycatch avoidance efforts developed for the sea scallop fishery (O'Keefe *et al.*, 2010). Fishery participants were able to utilize the compiled spatial bycatch information to avoid the specific regions of traditional fishing grounds without reducing the catch of target species in January through March 2011. Vessels moved away from areas identified with high bycatch to areas with lower bycatch without significantly disrupting fishing operations. Eight of nine active fishing vessels used the information in its pilot phase, providing information about the avoidance programme to compare with the proposed area closures. The comparison indicates that there would have been a spatial mismatch between bycatch and closure areas, which would have shifted effort to regions with lower catch per unit effort of the target species without any significant reduction in bycatch (Bethoney *et al.*, 2013). The proposal for a costly time/area closure may have provided the incentive for the midwater trawl fleet to participate in the avoidance programme, and data collected through the pilot phase of the programme could help to refine management options for alosine bycatch reduction. The programme was expanded after the pilot phase to the Gulf of Maine in September and October 2011 and continued in the Mid-Atlantic Bight in January and February 2012 (Bethoney *et al.*, 2012). Results of the programme expansion suggest that the alosine bycatch avoidance programme meets criteria 1 through 4. There is evidence of a spatial separation of bycatch and target species, allowing the fishery to reduce alosine bycatch, maintain optimal catch levels of target species, avoid interactions with bycatch of other non-target species, and minimize negative effects of spatial effort shifts. The programme is currently maintained with grant funding which could jeopardize the long-term sustainability.

Fleet communication programmes can reduce bycatch and discards in a variety of fisheries. However, the success of these programmes relies heavily on fleet incentives. Most communication programmes develop as an alternative to costly time/area closures or early fishery closures resulting from bycatch caps and quotas (O'Keefe and Cadrin, 2011). It may be necessary to combine a variety of bycatch mitigation techniques to incentivize individual fishers to share catch information with other industry members, managers, or third-party organizations. The Alaskan longline demersal fishery relied on fleet communications in combination with altered fishing behaviour and gear regulations to reduce bycatch, whereas the Atlantic midwater trawl fleet incorporated increased levels of port-side and at-sea sampling to define smaller spatial regions for bycatch avoidance. Additionally, if only a fraction of a fleet participates in the programme, in both sharing information and following advice from communications, the effectiveness of the programme is reduced. As noted in the Sea State example, bycatch was reduced in the rock sole fishery but not in the yellowfin sole fishery due to participation levels. The TurtleWatch programme provided accurate information on the location of turtle aggregations, however, was not successful in reducing turtle interactions with longline vessels due to the lack of fishery participation. These examples demonstrate the advantages and disadvantages of utilizing fleet communication to reduce bycatch and discards and emphasize the need for strong incentives for high levels of fleet participation.

Discussion

A synthesis of the evaluation of each of the presented case studies shows some patterns that aid in determining the overall effectiveness of each of the reviewed mitigation techniques (Table 1). Of the five time/area closure programmes that were reviewed, only one programme (bycatch closures in the Kuwait shrimp fishery; Ye *et al.*, 2000) met more than one evaluation criteria. Three programmes were unsuccessful in reducing the intended bycatch, and despite reductions in juvenile plaice discarding reported from the plaice box (Pastoors *et al.*, 2000), the negative ecological consequences of the programme far outweighed the benefits. Both of the programmes that focused on a reduction in marine mammal bycatch (Murray *et al.*, 2000; Chilvers, 2008) only met criterion 3, no or minimal effect on the catch of other non-target species or sizes. In both cases, the size of the closure area was inadequate to meet bycatch reduction goals; however, a larger closure would render the programme economically unviable. Under these circumstances, a different mitigation strategy may be necessary. The programmes that focused on reducing finfish bycatch had mixed success. The shrimp closure example provides evidence that when designed appropriately, time/area closures can be effective. In contrast, the scup closures for the *Loligo* fishery did not reduce bycatch and actually created new bycatch issues outside of the closure areas (Powell *et al.*, 2004). The mixed results from the evaluation of time/area closures as an effective bycatch mitigation technique suggest

Table 1. Evaluation of bycatch mitigation programmes.

Bycatch mitigation programme	Reduced bycatch	Min. effect on target catch	Min. effect on non-target	No effort impacts	Economically viable
Time/area closures					
Shrimp in Kuwait (Ye *et al.*, 2000)	✓	✓	✓	✓	N/A
Porpoise in Gulf of Maine (Murray *et al.*, 2000)			✓		
Juvenile plaice in North Sea (Pastoors *et al.*, 2000)	✓		N/A		N/A
Scup in squid trawls (Powell *et al.*, 2004)					
New Zealand sea lions (Chilvers, 2008)			✓		
Quotas/caps					
Sea scallop bycatch cap (O'Keefe *et al.*, 2010)					
Canada trawl ITQ (Diamond, 2004; Branch *et al.*, 2006)	✓	✓	✓	✓	N/A
New Zealand Quota Management (Lock and Leslie, 2007)	✓	✓		✓	✓
Fleet communication					
Sea State Inc. rocksole fishery (Gauvin *et al.*, 1995)	✓	✓	✓	✓	✓
Sea State Inc. yellowfin sole fishery (Gauvin *et al.*, 1995)		✓	✓	✓	
TurtleWatch Hawaii longline (Howell *et al.*, 2008)		✓	✓	✓	
Fisheries Information Services (Gilman *et al.*, 2006)	✓	✓	✓	✓	✓
Alosines in midwater trawl (Bethoney *et al.*, 2013)	✓	✓	✓	✓	
Combined holistic strategy					
Seabirds in Southern Ocean (Croxall, 2008)	✓	✓	✓	✓	✓

Evaluation criteria include (1) reduced identified bycatch or discards, (2) no or minimal negative effect on the catch of target species, (3) no or minimal negative effect on the catch of other non-target species or sizes, (4) no or minimal spatial or temporal displacement of bycatch, and (5) economically viable for the fishery. ✓, evaluation criteria met; blank, evaluation criteria not met; N/A, evaluation criteria not evaluated.

that significant research about the location and level of bycatch on various spatial and temporal scales is required before implementation.

The bycatch quota and cap programmes that were reviewed had vastly different results with respect to effectiveness. The yellowtail flounder bycatch cap in the scallop fishery did not meet any of the evaluation criteria due to programme design (O'Keefe *et al.*, 2010). The fleet wide cap created a derby-style fishery with no individual accountability and resulted in early fishery closures. Conversely, the British Columbia quota system, which included individual accountability, significantly reduced bycatch without leading to unintended consequences (Diamond, 2004). The New Zealand Quota Management System met most of the evaluation criteria, but caused changes in fishing behaviour resulting in unexpected shifts in targeting of certain species. Although bycatch caps are an accepted mitigation technique globally, there are few examples that provide evidence of their success when not combined with other incentive-based or gear modification techniques. While individual quota systems can aid in bycatch reduction, very few programmes have been established specifically for this purpose. A more thorough investigation of the utility of quotas and caps to effectively reduce bycatch is warranted, because fishery management systems around the world have moved towards output controls for all managed species (Pope, 2002; Beddington *et al.*, 2007).

All the fleet communication programmes that were reviewed met criteria 2, 3, and 4. By nature, the implementation of a fleet communication programme requires participation and collaboration from the fishing industry (Gilman *et al.*, 2006). Industry members can often provide valuable insights about fishing techniques that enable them to reduce bycatch without effecting target catch (i.e. hanging a scallop dredge just under the surface of the water to release flatfish before bringing the catch onboard the vessel; E. Welch, *F/V Westport*, pers. comm.) or towing an otter trawl at faster speeds to reduce flatfish bycatch when targeting gadoids (F. Mattera, *F/V Travis & Natalie*, pers. comm.). Incorporating fishers' knowledge of fishing techniques can aid in designing mitigation programmes that maintain target catch, minimize impacts on the bycatch of other non-targeted species, and reduce negative impacts from shifts in fishing effort. Fleet communication programmes likely would not be effective in meeting these criteria without input from the fishing industry. Fishers participation in communication programmes is related to the level of industry input in programme design. As noted in the Sea State example, results from fleet communications can be variable, depending on the level of participation (Gauvin *et al.*, 1995). TurtleWatch provided accurate advice on the location of turtle aggregations, but the fleet ignored the information (Howell *et al.*, 2008). Without strong incentives to reduce bycatch, voluntary fleet communications can easily fail to meet objectives. The threat of time/area closures and bycatch caps provided strong incentive to the midwater trawl fleet to reduce alosine bycatch (Bethoney *et al.*, 2013). Similarly, a repeated pattern of early closure of the Alaska longline fleet prompted the fishery to share effort data and follow bycatch advisories (Gilman *et al.*, 2006). Fleet communication programmes can be economically viable when the fishing fleet funds or assists with programme costs. The costs of data sharing are typically low compared with the value of the commercial catch as noted in the Alaska longline programme to reduce seabird and halibut bycatch (Gilman *et al.*, 2006), and the value added to fisheries by extending seasons and expanding areas that are open can be considerable (Gilman *et al.*, 2006; O'Keefe *et al.*, 2010).

Considering the results of the evaluation for all three mitigation techniques together provides conclusions about the strengths and weaknesses of the various approaches and how the techniques could be combined to enhance effectiveness. Time/area closures and bycatch caps have promoted strong incentives to reduce bycatch and incorporate individual accountability. If used in combination with fleet communication programmes or individual quotas, these measures may be more effective in meeting programme objectives. Any of the reviewed measures could be used in combination with gear modifications to increase the selectivity of target species and reduce incidental catch. This holistic approach to bycatch reduction requires wide-ranging studies of species' life histories, potential changes in fleet behaviour, and individual incentives.

Reduction in seabird bycatch in the Southern Ocean through efforts by the Commission for the Conservation of Antarctic Marine Living Resources (the Commission) provides an example of a holistic approach to mitigating bycatch. Albatross populations on the Antarctic continent began declining in the 1970s, with rapid decline in the 1980s. Data related to productivity, fecundity, and survival indicated that the main causes of mortality were likely occurring at sea (Croxall, 2008). Direct observations of interactions between albatrosses and longline fisheries suggested that a large proportion of adult females were being killed on longlines, because the birds were attracted to the baited hooks then pulled under water and drowned. The Commission convened a meeting of experts on seabird mortality in longline fisheries to provide advice on potential mitigation measures to reduce seabird bycatch in 1993. They created a Working Group related to incidental mortality from longline fishing that met simultaneously with the Working Group on Fish Stock Assessment to ensure any mitigation recommendations were endorsed by both groups (Croxall, 2008). The Commission required longline vessels to carry a scientific observer, and they provided outreach materials to longline vessels to raise awareness of the bycatch problem. The Commission also used a suite of mitigation measures, including prohibiting offal discharge so birds would not be attracted to vessels, use of streamers on sinking lines to scare birds, use of weighted lines to sink faster, prohibiting line setting during daylight hours, and seasonal restrictions to coincide with bird migration patterns. Within 4 years of the implementation of the mitigation measures, seabird bycatch was reduced by an order of magnitude. Through further collaboration between the fishing industry, managers, scientists, and observers, bycatch was reduced to less than 1% of the original estimate (from 5755 birds in 1997 to 21 birds in 2000) and has remained low in recent years (0 birds in 2006; Croxall, 2008).

Reduction in seabird bycatch in the Southern Ocean was successful because several factors were considered in developing mitigation strategies, including target species catch, outreach to fishing industry members, compliance levels, and economic feasibility. The high value of the Patagonian toothfish and tuna longline fisheries offset costs to implement gear modifications, and collaborative research involving fishers and scientists provided practical, cost-effective solutions to reduce bycatch without impacting the catch of target species (Croxall, 2008). Inclusion of multiple stakeholders in data assessment and management advice increased the awareness of the bycatch issues and provided a forum for compromise to increase compliance in bycatch regulations. Combining time restrictions (setting at night) and spatial restrictions (seasonal closures of regions overlapping with bird migration patterns) with gear modifications resulted in substantial bycatch reduction without disproportionately impacting any single faction of the fishery (Croxall, 2008). The Commission employed an iterative approach to implementing the bycatch mitigation strategies, incorporating feedback loops, and stakeholder input throughout the process. The Commission's approach for reducing seabird bycatch, developed and implemented over the course of more than a decade, met all the evaluation criteria as an effective bycatch mitigation strategy.

Conclusions

Although many of the reviewed programmes have been successful in reducing bycatch and discarding, most reported unanticipated results related to shifts in fishing effort, changes in catch of non-target species, reduced catch of target species and socio-economic impacts to the fishing fleets (Table 1). Our review focused on peer-reviewed evaluations of mitigation techniques, which are representative of each of the bycatch mitigation methods. We recognize that there are many mitigation programmes globally; however, most have not been formally evaluated against a set of performance criteria. Many of the programmes concluded that further study of species' life histories, potential changes in fleet behaviour, and individual incentives was necessary before implementing a specific type of mitigation technique. The majority of studies suggested combining a suite of mitigation techniques to reduce bycatch and discarding was more effective than applying a single measure. Additionally, some of the case studies emphasized that collaborative programmes, which utilize the skill sets of fishers, scientists, and managers, have been more effective in meeting bycatch reduction objectives. The synthesis of our evaluation suggests that a holistic approach, incorporating an understanding of the unintended consequences that arise from various mitigation techniques, may be the most beneficial way to move forward in global bycatch reduction.

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