Reviews in Fisheries Science & Aquaculture

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/brfs21

Efficacy of Time-Area Fishing Restrictions and Gear-Switching as Solutions for Reducing Seabird Bycatch in Gillnet Fisheries

Catherine E. O'Keefe, Steven X. Cadrin, Gildas Glemarec & Yann Rouxel

To cite this article: Catherine E. O'Keefe, Steven X. Cadrin, Gildas Glemarec & Yann Rouxel (2021): Efficacy of Time-Area Fishing Restrictions and Gear-Switching as Solutions for Reducing Seabird Bycatch in Gillnet Fisheries, Reviews in Fisheries Science & Aquaculture, DOI: 10.1080/23308249.2021.1988051

To link to this article: https://doi.org/10.1080/23308249.2021.1988051

Published online: 07 Oct 2021.

REVIEWS IN FISHERIES SCIENCE & AQUACULTURE
https://doi.org/10.1080/23308249.2021.1988051

Routledge
Taylor & Francis Group

REVIEW

Efficacy of Time-Area Fishing Restrictions and Gear-Switching as Solutions for Reducing Seabird Bycatch in Gillnet Fisheries

Catherine E. O'Keefe[a], Steven X. Cadrin[a,b], Gildas Glemarec[c] and Yann Rouxel[d]

[a]Fishery Applications Consulting Team, Dartmouth, Massachusetts, USA; [b]School for Marine Science and Technology, University of Massachusetts Dartmouth, New Bedford, Massachusetts, USA; [c]National Institute of Aquatic Resources, Technical University of Denmark, Lyngby, Denmark; [d]Royal Society for the Protection of Birds, Scotland, UK

ABSTRACT

Despite the global scale of gillnet bycatch, universal measures that effectively reduce bycatch of seabirds in gillnets have not been found. Bycatch in coastal gillnet fisheries is an ongoing threat for several seabird species. Strategies to reduce seabird bycatch in gillnet fisheries were evaluated, focusing on the effectiveness of time-area fishing restrictions and gear-switching to meet seabird conservation objectives, ensure fisher acceptance, and avoid unintended consequences. A review of case studies showed that variations in the spatial and temporal distributions of target and non-target species may cause a mismatch between time-area regulations and high bycatch, but consideration of bycatch species behavior can help define effective fine-scale spatial and temporal measures. The potential for meeting conservation objectives through gear-switching is promising, with some further development needed for successful application. Combining measures (e.g., time-area fishing restrictions, gear-switching, visual and acoustic deterrents) may be feasible in some regions, if fine-scale spatial and temporal information about the overlap of seabirds and gillnet gear is available. A holistic approach to reduce seabird bycatch in gillnets, including understanding of seabird biology, habitat preference, and feeding ecology combined with information about fishing activity, target species, and socioeconomic impacts provides a framework to develop mitigation measures.

KEYWORDS
Bycatch; seabirds; gillnet; time-area; gear-switching

Introduction

Bycatch of seabirds in gillnet fisheries has been recognized as a conservation concern since the 1970s (Tull et al. 1972; King et al. 1979) with increased attention focused on estimating bycatch-induced mortality and bycatch mitigation measures over the last two decades (Bull 2007; Žydelis et al. 2013; Northridge et al. 2017). Despite the global scale of gillnet bycatch, management procedures that are generally effective for reducing bycatch of seabirds in gillnets have not been found (Žydelis et al. 2013; Wiedenfeld 2016; Field et al. 2019). Challenges to mitigating seabird bycatch in gillnets include the variety of birds susceptible to gillnet gear (Sonntag et al. 2012; Žydelis et al. 2013), the broad range of fishes targeted by gillnets (Almeida et al. 2017; Carneiro et al. 2020), and the diversity of gillnet fisheries (Northridge et al. 2017).

Seabirds serve an important role in marine ecosystems (Croxall et al. 2012) and have potential to serve as bioindicators of ecosystem health (Parsons et al. 2008; Durant et al. 2009). Nearly one third of all seabird species are globally threatened, and fisheries bycatch has substantially contributed to the decline in seabird populations (Dias et al. 2019). Bycatch of pelagic seabird species in longline and trawl fishing gears has been extensively studied (Lewison et al. 2005; Bull 2007; Croxall 2008; Anderson et al. 2011; Clay et al. 2019), assisted by data from large-scale, multinational industrial fisheries (Lewison et al. 2014). More recently, bycatch in small-scale, coastal gillnet fisheries has been identified as a threat to several seabird populations (Žydelis et al. 2009, 2013; Lewison et al. 2014; Almeida et al. 2017; Christensen-Dalsgaard et al. 2019; Marchowski et al. 2020).

At least 400,000 seabirds are killed in gillnets annually, including species that are critically endangered,

CONTACT Catherine E. O'Keefe okeefe@fisheryapps.com Fishery Applications Consulting Team, 99 Bakerville Road, Dartmouth, MA 02748 USA.

threatened, or vulnerable, and seabirds that forage underwater (e.g., cormorants, auks, shearwaters, penguins and seaducks) are most susceptible to gillnet bycatch (Žydelis et al. 2013). Recent studies suggest that gillnet bycatch is an important factor in population declines for several seabirds (Christensen-Dalsgaard et al. 2019; Dias et al. 2019), including the greater scaup (*Aythya marila*; Marchowski et al. 2020), the northern fulmar (*Fulmarus glacialis*; Baerum et al. 2019), several loon species (Bentzen and Robards 2014), the long-tailed duck (*Clangula hyemalis*; Bellebaum et al. 2013), the common eider (*Somateria mollissima)*, the king eider (*Somateria spectabilis*; Merkel 2011), the common guillemot (*Uria aalge*; Österblom et al. 2002; Regular et al. 2013), and several penguin species (Crawford et al. 2017). Seabirds are susceptible to bycatch in gillnets in nearly all parts of the world, with known hotspots in the Baltic, Northeast Atlantic, and Northwest, Northeast, and Southwest Pacific (Žydelis et al. 2013; Lewison et al. 2014). In comparison to these global and regional evaluations, much less information is available from coastal gillnet fisheries that operate from small boats but have high social, economic, and cultural importance for coastal communities (Allison and Ellis 2001; Villasante et al. 2015). The limited information from small-scale gillnet fisheries impairs understanding of the magnitude and severity of total bycatch mortality for coastal bird species (Lewison et al. 2014; Pott and Wiedenfeld 2017; Dias et al. 2019).

Increased awareness of the impacts of coastal gillnet fisheries on seabird populations has prompted research on potential bycatch mitigation measures (e.g., Žydelis et al. 2009; Sonntag et al. 2012; Bellebaum et al. 2013; Baerum et al. 2019; Glemarec et al. 2020). Designing effective bycatch mitigation programs requires an understanding of the life histories of target and bycatch species, interactions of species with fishing gears, effects of spatial and temporal shifts in fishing effort, socioeconomic impacts to the fishery, and incentives of fishery participants (O'Keefe et al. 2014). Specific mitigation measures, such as gear modifications, fleet communications, and bycatch quotas, are better-suited to some fisheries and gears than others and can result in unintended biological and socioeconomic consequences when applied inappropriately (Hamilton and Baker 2019; Food and Agriculture Organization (FAO) 2021; Orphanides and Palka 2013; Pace et al. 2014). Gear modifications and gear handling practices have been effective at reducing seabird bycatch for active fishing gears, such as longlines and trawls, based on the ability to observe interactions between birds and gear components during fishing activities (Croxall 2008; Bull 2009; Anderson et al. 2011; Løkkeborg 2011). Such technical measures have not generally been successful when applied to passive gears, including gillnets, because bycatch events typically occur when the gear is untended or underwater where interactions cannot be directly observed (Almeida et al. 2017; Hanamseth et al. 2017; Field et al. 2019; Cantlay et al. 2020). Similarly, fleet communication programs designed to reduce bycatch rely on real-time, or near real-time, observations and information sharing to avoid bycatch hotspots (Gilman et al. 2006; O'Keefe and DeCelles 2013; Bethoney et al. 2013a) and are not feasible for untended passive gears. Bycatch quotas are frequently applied to manage finfish bycatch (e.g., Abbott and Wilen 2009; Pascoe et al. 2010; Holland and Martin 2019) but are not considered an appropriate mitigation tool for protected and prohibited species, such as seabirds, marine mammals, and turtles, with some exceptions (Hall 1998; Bisack and Sutinen 2006). Quota management systems are most effective when combined with accurate fishery monitoring and strict enforcement, which are less common in small-scale, coastal fisheries (Lewison et al. 2014; Exeter et al. 2021).

Understanding the causes of seabird bycatch in gillnet fisheries can inform the types of mitigation measures that can effectively reduce bycatch. Northridge et al. (2017) reviewed case studies of gillnet bycatch of marine mammals, turtles and seabirds and identified four main influences of bycatch rates, categorized as environmental, operational, technical, and behavioral factors. For example, environmental factors such as water depth and temperature may be useful predictors of seabird bycatch that could inform spatial and temporal mitigation measures. The combined use of fishery and environmental data has been effective in reducing bycatch in several fisheries (Hobday and Hartman 2006; Bethoney et al. 2013b; Turner et al. 2016; Hazen et al. 2018; Lowman et al. 2021). Operational and technical factors, such as soak duration, diurnal gear setting, net height, and mesh size, may also affect seabird bycatch rates (Melvin et al. 1999; Almeida et al. 2017), and additional research on how to control these factors or explore alternative gear types is needed (Northridge et al. 2017).

Visual deterrents, including lights, contrast panels, oxidized nets, colored nets, and mesh thickness, have been evaluated for effectiveness in reducing seabird bycatch in gillnets (Almeida et al. 2017). Alcids (e.g., murres, guillemots, auklets, puffins, and murrelets) are often caught in the upper sections of gillnets after diving in response to being startled by the float line, and bycatch of alcids in the Puget Sound salmon gillnet fishery was reduced when high-visibility white monofilament meshes were incorporated in the top portion of the nets (Melvin et al. 1999). The white mesh was effective as a visual deterrent, but seabirds had varying reactions, and the target species catch was reduced (Melvin et al. 1999). Like alcids, cormorants are visual pursuit predators, which potentially can detect visual deterrents underwater (Martin and Crawford 2015). Bycatch of Guanay cormorants (*Leucocarbo bougainvillii*) in the eastern Pacific gillnet fishery was reduced with the use of green light-emitting diodes (Mangel et al. 2018). Field et al. (2019) tested the effectiveness of high contrast net panels and lights to reduce gillnet bycatch of diving seabirds in the Baltic Sea but found no significant reduction in bycatch of long-tailed ducks or velvet scoters (*Melanitta fusca*) from any of the visual deterrent configurations and observed an increase in bycatch of long-tailed ducks in nets equipped with white flashing lights. The diving seabirds of the Baltic region feed in low-light environments where visual cues are not easily detected (Martin and Crawford 2015). The mixed results from visual deterrents suggest that there is not a universal gear modification that will mitigate seabird bycatch in all gillnet fisheries. Therefore, species and region-specific mitigation measures that account for seabird behavior and marine environment conditions need to be considered.

Recognizing and incorporating perspectives and incentives of fishers toward bycatch reduction are key elements of successful mitigation strategies. Socioeconomic impacts that can result from bycatch reduction measures have been well-documented for data rich fisheries (Alverson et al. 1994; Crowder and Murawski 1998; O'Keefe et al. 2014; Komoroske and Lewison 2015), but less information on the impacts on coastal gillnet fisheries is available due to the small-scale, data-poor nature of these fisheries. Eliminating seabird bycatch may be an important societal objective or a governance directive (European Commission (EC) 2017; Lewison et al. 2004; Senko et al. 2014), but management strategies that recognize local constraints and opportunities, such as seasonal fishing effort and target species, may garner more support from fishers than broad regulatory mandates (Kirby and Ward 2014). The cumulative impacts of bycatch on bird populations are often not recognized by fishers because seabird bycatch events are relatively rare at the individual fisher level (Barz et al. 2020). Perceptions of seabird bycatch depend on fishing behavior, and operational aspects (e.g., fishing grounds, seasonality, costs, and profits) can influence acceptance of mitigation techniques (Lewison et al. 2011; Barz et al. 2020).

This review evaluated strategies to reduce seabird bycatch in gillnet fisheries, focusing on the effectiveness of certain tools to meet seabird conservation objectives, ensure fisher acceptance, and avoid unintended consequences. Examples of time-area fishing restrictions and gear-switching strategies that have been applied to reduce bycatch of seabirds and other taxa were reviewed with respect to a set of evaluation criteria including: 1) measurable reduction of bycatch; 2) minimal effect on the catch of target species; 3) minimal effect on the catch of other non-target species; and 4) effective implementation. The reviewed case studies include bycatch mitigation in small-scale gillnet fisheries from regions where information was available, supplemented by relevant examples from other fisheries. Most of the case studies have been peer-reviewed with respect to the evaluation criteria, and others were reported through gray literature and technical reports. The general findings from the review are intended to guide future research and applications but results of the evaluation may not characterize all potential outcomes for small-scale gillnet fisheries as the reviewed case studies do not include the entire range of gillnet fisheries that interact with seabirds or all examples of time-area restrictions and gear-switching.

Methods

The evaluation was based on in-depth reviews of case studies that included analyses of applied bycatch mitigation tools. Results from each case study were examined to determine if the mitigation strategy met the evaluation criteria. To meet the first criterion, measurable reduction of bycatch, the implemented mitigation tool resulted in a reduction in bycatch rates or numbers. The second criterion, minimal effect on the catch of target species, was met when the implemented tool did not result in substantial changes in catch rates of target species, positively or negatively, and did not substantially change target species catch composition. To meet the third criterion, minimal effect on the catch of other non-target species, there were minimal changes in bycatch or discard ratios for species other than the intended bycatch species after the mitigation tool was implemented compared to before. The fourth criterion, effective implementation, was met if the mitigation tool a) was applied to a fishery beyond experimental phases, b) was monitored for long-term efficacy in meeting the first three criteria, and c) was considered acceptable by fishers as demonstrated through uptake and enforceability. Information related to each criterion varied across the case studies. No attempt was made to evaluate criteria that were not explicitly addressed in the reviewed literature, instead general conclusions from studies that met one or more of the performance criteria are described.

Few examples of experimental trials to assess time-area fishing restrictions and gear-switching to reduce seabird bycatch in gillnet fisheries exist because these are relatively new research topics. In addition to case studies, the review included examples of bycatch reduction tools, highlighting information to support time-area restrictions and gear-switching, such as visualization tools, predictive bycatch modeling, and incentive-based approaches. The analyses are grouped according to mitigation tool (time-area fishing restrictions and gear-switching) and case study type (applied measures and supportive tools).

Time-area fishing restrictions

Spatial and temporal restrictions on fishing may reduce bycatch, effectively removing the fishing gear from interactions with non-target species. Time-area restrictions can be implemented with relatively simple regulations but determining the appropriate scale to meet bycatch reduction objectives and minimize economic impacts can be difficult (O'Keefe et al. 2014). Large-scale and long-term closures protect ecosystem components inside the closure but can lead to shifts in fishing effort that may increase bycatch issues or create new impacts (Walters 2000; Keith et al. 2020). Fine-scale restrictions may minimize negative economic impacts to fishers but are highly data-dependent and rely on strong monitoring and enforcement systems to be effective (Dunn et al. 2011; Hazen et al. 2018). Examples of time-area fishing restrictions were evaluated to examine strengths and weaknesses in program design for meeting conservation objectives and ensuring effective implementation. Three case studies of time-area restrictions directly applied for seabird bycatch mitigation in coastal gillnet fisheries (Puget Sound salmon gillnet fishery, Canadian cod and salmon gillnet fishery, and California set net halibut and croaker fisheries) were reviewed. Additionally, recent efforts that map and model seabird bycatch, which could be applied to develop fine-scale spatial and temporal measures, were considered.

Puget sound salmon gillnet fishery

Mitigation tools to reduce bycatch of alcids (common murre, *Uria aalge,* and rhinoceros auklet, *Cerorhinca monocerata*) were tested in the drift gillnet fishery targeting Pacific salmon species in Puget Sound. Melvin et al. (1999) documented seabird and salmon abundance-entanglement relationships over two fishing seasons in 1995 and 1996. Examination of bycatch rates throughout the fishing seasons and during daily operations suggested a temporal relationship between salmon catch and seabird bycatch rates. Murre bycatch was high at the end of the fishing season when salmon catch was lowest and auklet bycatch was moderate in the middle of the season as salmon catch rates began to decline after the initial fishery opening. Local abundance of the common murre varied greatly during the study period (~5,000 in 1995 and ~30,000 in 1996) related to factors that affected breeding timing, whereas local abundance of rhinoceros auklet was relatively constant. The authors suggested that fishery openings could be scheduled based on peak salmon abundance to reduce potential interactions with seabirds.

Diel variation in bycatch was also observed, with higher seabird entanglement during dawn operations. Results showed that 60% of auklet and 30% of murre entanglements could be eliminated with only 5% reduction in salmon catch by prohibiting fishing during dawn hours (Melvin et al. 1999). Seabird bycatch could be reduced by up to 75% while achieving salmon catch allocations with a combination of bycatch mitigation tools, including highly visible mesh panels in the upper portion of the net, time of day restrictions, and abundance-based fishery openings, and the greatest single reduction in bycatch (43%) could result from limiting the fishing season to periods of high salmon abundance (Melvin et al. 1999). The case study demonstrates that temporal fishing restrictions, both seasonally and daily, could reduce seabird bycatch in the salmon gillnet fishery, and fisher collaboration to develop mitigation approaches can reduce economic impacts. Since 1997, management of Puget Sound commercial salmon fisheries has included some of the recommended seabird bycatch reduction tools tested by Melvin et al. (1999). Currently, regulations include gillnet gear specifications and time of day fishing restrictions to provide protection to seabirds (Washington Department of Fish and Wildlife (WA DWF) 2020).

Canadian cod and salmon gillnet fishery

In 1992, the gillnet fisheries targeting northern cod (*Gadus morhua*) and Atlantic salmon (*Salmo salar*) off eastern Canada were closed to rebuild populations of both species (Myers et al. 1997). Regular et al. (2013) examined the effects of gillnet removal on seabird populations by comparing population trends of diving and surface-feeding birds before and after the fishing moratoria were implemented. Gillnet fishing substantially decreased in inshore seabird foraging areas after the moratoria, with only limited seasonal gillnet fishing effort remaining. Coinciding with diminished gillnet effort, populations of diving seabirds increased, and abundance of surface-feeding birds decreased. The common murre population increased at a greater rate following the closure, whereas the herring gull (*Larus argentatus*) population decreased. The observed trends were attributed to substantial reductions in bycatch mortality for common murres, and reduced breeding success of herring gulls resulting from the elimination of discards and offal from fishing activities (Regular et al. 2013). A consequence of shifting gillnet effort from inshore to offshore areas was incidental takes of shearwater species in the offshore fishery (Benjamins et al. 2008). Regular et al. (2013) concluded that the large-scale reduction in gillnet fishing effort resulting from the closures had widespread effects on seabird populations, including reduced gillnet bycatch mortality that allowed for population growth of diving seabirds, reduced food availability from discarded fish that reduced abundance of surface-feeding seabirds, and shifts in fishing effort that created a new bycatch issue for pelagic seabirds.

California set net halibut and croaker fisheries

Bycatch in set nets used to target California halibut (*Paralichthys californicus*) and white croaker (*Genyonemus lineatus*) in coastal California contributed to a substantial decline of the common murre population in the early 1980s (Wild 1990). As set net fishing effort increased in 1980, there were large numbers of dead seabirds washing ashore. An estimated 20,000 seabirds drowned in set nets during a 14-month period from June 1980 to August 1981, prompting the first in a series of inshore closures to set net fishing. State regulations and legislative actions prohibited the seasonal use of gillnets and trammel nets in depth-specific fishing zones between 1981 and 1987. At-sea monitoring indicated that seabird bycatch was reduced in some areas, but set net effort remained high and continued to shift to areas around the closures. In 1987, legislation prohibited the use of set nets in some inshore areas, which further reduced local bycatch, but continued effort shifts and weakened regulations over the next two years resulted in increased bycatch rates.

The emergency and permanent inshore zonal closures reduced seabird bycatch and total mortality, but these measures were not as effective as desired (Wild 1990). The distribution of forage fishes that several diving seabirds rely on varied seasonally and interannually, and the areas of elevated seabird bycatch risk shifted accordingly. In turn, the spatial management efforts were impeded, and total seabird mortalities continued at unacceptable levels over the 1980s (Wild 1990). Considering the continued high seabird mortality from set net bycatch from the previous decade, more stringent permanent closures of inshore waters to a depth of 55 m were implemented in 1991. Estimated average gillnet mortality of common murres was reduced from ~10,000 murres per year in the 1980s to the low thousands of birds per year between 1990 and 1998 (Forney et al. 2001). Therefore, it appears that the permanent inshore set net closures were effective in reducing seabird bycatch mortality. The lack of recovery of two breeding colonies, however, suggests that bycatch mortality may still have been affecting species recovery in coastal California a decade after the permanent closures were implemented (Forney et al. 2001).

Mapping and modeling of spatial and temporal seabird-fisheries interactions

Successful application of spatial and temporal fishing restrictions is primarily dependent on understanding the overlap of target and non-target species. Unfortunately, information about total fishing effort, seasonal catch composition, and bycatch rates is limited for many coastal gillnet fisheries (Žydelis et al. 2013; Lewison et al. 2014; Glemarec et al. 2020). Recent studies that provide fine-scale spatial and temporal seabird distribution and abundance estimates in areas where gillnets are fished could be useful to design time-area fishing restrictions (Sonntag et al. 2012; Bellebaum et al. 2013; Baerum et al. 2019; Glemarec et al. 2020). The development of tools to predict outcomes of potential time-area restrictions also provides a framework for understanding data requirements, effectiveness of measures in meeting objectives, and potential acceptance from fishers (van Beest et al. 2017; Sherley et al. 2018; Barz et al. 2020).

Sonntag et al. (2012) developed a tool to visualize spatial and temporal overlap between seabirds and gillnets in a portion of the German Baltic coast. They found patterns of overlap related to water depth and season and suggested that time-area fishing restrictions may be useful to reduce seabird bycatch. Bellebaum et al. (2013) estimated bycatch of seabirds along the German Baltic coast and found that fishing effort and numbers of bycaught seabirds varied considerably between months and fishing fleets, with bycatch probability decreasing in deeper waters during summer months. The number of seabirds caught was related to fishing effort and possibly affected by net length, with greater bycatch in longer nets used for pikeperch (*Sander lucioperca*) compared to shorter nets used to target herring (*Clupea harengus*; Bellebaum et al. 2013). A 20-year time series of seabird abundance data showed that bycatch rates were dependent on bird densities and followed seasonal and spatial patterns. The authors concluded that bycatch rates for diving seabirds were greatest during winter and spring in shallow water and lowest in summer in deeper waters, and that bycatch in lagoons with large densities of seaducks was relatively high compared to other areas (Bellebaum et al. 2013). They noted a decline in seabird bycatch in recent years associated with the decline in numbers of overwintering birds and a decrease in the number of fishermen that had been displaced by cod regulations. They recommended targeted effort reductions and possible gear-switching to reduce seabird bycatch along the German coast but noted that the ability to avoid bycatch may be constrained by fishing patterns that have evolved to maximize catch of highly regulated target species. Furthermore, the authors suggested that temporary spatial closures may reduce bycatch of diving seabirds in specific bird staging areas, but more extensive closures that could negatively impact fishers would be needed in lagoons and shallow coastal areas throughout the winter season to meet conservation objectives (Bellebaum et al. 2013). Although these studies did not include recommendations for specific time-area fishing restrictions, they provided fine-scale spatial and temporal information about seabirds and fishing activity that could be valuable for predicting potential outcomes from such a mitigation program.

An in-depth analysis of spatial and temporal variation in seabird bycatch was conducted in the Norwegian coastal gillnet fishery. Baerum et al. (2019) applied a modeling approach to determine what factors affect bycatch rates, including seabird feeding behavior, season, area, depth, and distance to shore. Data from the coastal gillnet fleet between 2006 and 2015 indicated that 2% of all fishing trips reported seabird bycatch and 85% of the bycatch events consisted of five birds or less. Due to the high variability in the distribution of fishing effort over a large area, extrapolations of observed bycatch rates to the entire fleet resulted in relatively large and widespread annual seabird bycatch estimates, ranging from 1,580 to 11,500 birds (Baerum et al. 2019). Results showed an even proportion of diving and surface-feeding seabirds in net catches but with distinct spatial and temporal bycatch patterns. Bycatch rates of diving seabirds were highest in northeast Norway, in shallow depths, close to shore, and during winter (November to January). Bycatch rates of surface-feeding seabirds were also higher in northeast Norway and in May and June (Baerum et al. 2019). The authors suggested that time-area fishing restrictions may be an effective bycatch mitigation tool for diving seabirds in the Norway coastal gillnet fishery due to the relationship between bycatch, fishing depth, and distance from shore in winter months. They indicated that gear modifications and alternative gear handling techniques may be more effective than fishing restrictions for surface-feeding seabirds despite the distinct spatiotemporal distribution because mortality is related to net setting and offal discharge (Baerum et al. 2019). This information about seabird behavior and fine-scale spatial and temporal distribution patterns of birds and fishing activity is critical for designing effective mitigation strategies that combine multiple tools across fisheries.

Predictive models that examine potential outcomes of time-area fishing restrictions can be useful for data-limited scenarios and consideration of tradeoffs when designing measures that impact fishing activities. For example, Sherley et al. (2018) modeled long-term productivity of African penguins (*Spheniscus demersus*) by examining short-term changes in seabird survival, condition, and population growth rate to assess the effectiveness of fishery closures designed to increase populations of seabirds that rely on forage fish. They found no significant change in chick condition in three of four study sites, but chick survival increased by ~11% throughout the range of the fishery closures. Long-term population growth increased by >1% and met biological objectives in a portion of the closure areas, but the forecasts projected a continued reduction of the penguin population under all management scenarios (Sherley et al. 2018). The authors also noted that the closures resulted in economic impacts to fishers with a reduction in total catches up to 9%, and they suggested that small-scale fishery closures should be used in combination with a suite of management tools to increase the chances of conservation success.

Van Beest et al. (2017) developed spatially explicit individual-based simulation models to evaluate effectiveness of acoustic deterrents (pingers) and time-area fishing restrictions to reduce bycatch of harbor porpoises (*Phocoena phocoena*) in gillnet fisheries. Pingers have effectively reduced cetacean bycatch (Dawson et al. 2013), but they have potential to impact foraging behavior (van Beest et al. 2017). Time-area restrictions may be a useful tool to reduce harbor porpoise bycatch, but experiences in the Gulf of Maine showed that the required closure to meet conservation objectives resulted in major impacts on fishing practices with negative economic consequences (Murray et al. 2000; O'Keefe et al. 2014). Van Beest et al. (2017) modeled harbor porpoise population size in Danish waters under several scenarios, including no bycatch mitigation measures, use of pingers only, use of time-area restrictions only, and combined use of pingers and time-area restrictions. They found that pingers alone were not sufficient to reduce the harbor porpoise population long-term decline and that time-area restrictions without the use of pingers could result in increased bycatch outside of closed regions. Modeling results suggested that the combined use of pingers and time-area restrictions could meet conservation objectives for harbor porpoise populations while maintaining fishing activities (van Beest et al. 2017). The authors concluded that spatially explicit, behavior-based models can assist managers in evaluating potential long-term impacts of different mitigation strategies.

Although predictive models can be useful to examine potential outcomes from time-area fishing restrictions, consequences associated with single species management objectives need to be considered. Copello et al. (2016) examined the distribution, bycatch rates, and foraging behavior of seabirds inside and outside of the Argentine hake closure to determine the impacts of a 'boundary effect' from concentrated fishing effort. The Argentine hake fishery closure, a ~120,000km^2 fishery exclusion area on the Patagonia shelf, was implemented in the mid-1990s to protect Argentine hake (*Merluccius hubssi*). Since the 1997 ban on trawl gear, hake and other fish stocks substantially increased in the closure area (Copello et al. 2016). Fishing effort that was concentrated on the closure boundary, however, resulted in increased bycatch of several albatross and petrel species. They analyzed the relationship between seabird bycatch and distance of vessels from the closure boundary and found that most seabird interactions with trawlers occurred in clustered aggregations along the boundary line. They also found more intense foraging of black-browed albatross (*Thalassarche melanophris*) and southern giant petrel (*Macronectes giganteus*) near the closure boundary than away from it or inside the closure area (Copello et al. 2016). The authors noted that there are no oceanographic fronts (i.e., areas with high productivity that typically attract seabird foraging) along the closure boundary and that the increased foraging was not associated with natural prey items. Albatross and petrel species are attracted to feed on discards and net spillage from fishing vessels (González-Zevallos and Yorio 2006; Pierre et al. 2012; Orben et al. 2021), so the fishery closure created a boundary effect of increased seabird bycatch associated with concentrated fishing effort. The authors highlighted potentially disproportionate impacts on juvenile seabirds resulting from competition for fishery discards with larger more aggressive adults, as well as female seabirds that are restricted to foraging in the Continental Shelf during the breeding period. Therefore, Copello et al. (2016) recommended that non-target species behavior and boundary effects should be considered when designing spatial conservation measures. The case study highlights problems with time-area closures that are designed to meet single species objectives and demonstrates how spatial shifts in fishing effort can impact ecosystem functions.

Gear-switching

Certain fishing gears have demonstrated detrimental effects on ecosystems through selective fishing, degradation of benthic habitats, and incidental bycatch of non-target species (Bastardie et al. 2021). In some situations, changing gear type may increase average income for fishers while reducing ecosystem impacts (Chuenpagdee et al. 2003; Rouxel and Montevecchi 2018). Gear substitutions, collectively referred to here as 'gear-switching', can be short-term or permanent (Jenkins and Garrison 2013). Although gear-switching has the potential to reduce bycatch of some species, economic and ecological tradeoffs should be evaluated before and after implementation. Gear-switching that reduces bycatch rates can save time and costs on the water if target catch is not affected, and certain gears can increase product quality resulting in higher sales prices (Broeg 2007). Constraining factors for gear-switching include the inability to maintain target catch rates, resistance to change from the fishing community, a lack of incentives for fishers to change their gear, and potential safety concerns (Food and Agriculture Organization (FAO) 2010). Examples of gear-switching were evaluated to demonstrate aspects that may be effective for reducing seabird bycatch in gillnets and to consider potential pathways and challenges to implementation. Two case studies of gear-switching to reduce seabird bycatch in coastal gillnet fisheries (California halibut fishery and Baltic cod fishery) were reviewed. Additionally, summarized knowledge gleaned from prior reviews on the general concept of gear-switching was considered.

California halibut fishery

Options for gear-switching for the gillnet fishery targeting halibut in coastal California were driven by severe economic impacts resulting from time-area closures enacted to reduce seabird and mammal bycatch (Haseltine and Thornton 1990; see above section on Time-Area Fishing Restrictions - California Set Net Halibut and Croaker Fisheries). As an alternative and supplement to time-area restrictions, the state of California explored substitute gears, including trawls, seines, traps, and lines, for efficiency and economic feasibility in catching halibut with minimal bycatch of non-target species. Trials showed that halibut catch was maintained by switching to otter trawl gear without any observed seabird bycatch in over 1,100 tows during the two-year study period (Haseltine and Thornton 1990). Bycatch of other non-target species consisted mainly of other flatfishes and elasmobranchs, most of which were returned to the ocean unharmed. The authors concluded that all the tested gear types reduced bycatch of seabirds and mammals, but only otter trawl gear caught halibut at rates similar to or exceeding set net gear (Haseltine and Thornton 1990).

Otter trawls had higher catch efficiency than gillnets, with the potential to land nearly three times as much halibut annually. Because of their high efficiency, regulators required the gears to be "scaled down", consisting of smaller trawl doors and shorter footropes. These regulations rendered the gear-switch infeasible for a portion of gillnet fishers with large vessels who were displaced from the closed areas. The greater efficiency of trawl gear also provoked opposition from recreational fishing groups based on concerns that nearshore trawling could deplete inshore resources (Haseltine and Thornton 1990). In 1992, legislative actions significantly reduced the use of gillnets in California state waters, and trawl gear has been the primary producer of halibut catch since then. To account for the high catch efficiency in trawl fisheries, several technical measures have been developed that limit the time and area of fishing operations, restrict the number of permitted participants, and regulate gear configurations (Frimodig et al. 2008). Since the enaction of the new set of rules, the California otter trawl halibut fishery has maintained low levels of seabird and marine mammal bycatch (California Ocean Science Trust (CA OST) 2013).

Baltic cod fishery

In the eastern Baltic Sea, along the coasts of Lithuania and southwest Latvia, seabird bycatch in the cod gillnet fishery was among the highest reported in the region in the late 2000s (Vetemaa and Ložys 2009). Approximately 10% of all wintering birds in Lithuanian coastal waters became entangled and died in gillnets each year, including long-tailed ducks, velvet scoters, and Steller's eiders (*Polysticta stelleri;* Žydelis et al. 2009). Over four winters, experimental longlines were set in proximity to gillnets in three locations to evaluate the effectiveness of gear-switching to reduce seabird bycatch without impacting target catch (Vetemaa and Ložys 2009). Researchers partnered with local fishers to design and build experimental longlines, which were tested by the research team for two consecutive seasons before being used by fishers for the next two seasons. Sea trials consisted of setting longlines parallel with gillnets in the same locations and depths, with the same set and haul times. Time needed to prepare and set both gear types was recorded, and total catch of the gears was compared (Vetemaa and Ložys 2009). Results showed increased catch of cod in longlines of comparable size and handling time to gillnets, with similar catches of sublegal sized cod and other non-target fish species. The experimental longlines did not catch seabirds during the study, but the paired gillnet sets caught only two birds over the course of the trials, barring conclusions about bycatch reduction. Fishers noted that setting and hauling longlines was no more difficult than setting gillnets, taking an average of ~20 minutes to set 100 hooks or 100 m of nets. The authors concluded that longlines may be an effective gear for small-scale fishers in the study area, but mechanical haulers would be needed for the larger scale operations to reduce handling time.

Although results were generally positive, the increased catch efficiency of longlines compared to gillnets (i.e., nearly three times higher catch rates) could impact the cod resource, and gear-switching would need to be limited according to the availability of cod in the region (Vetemaa and Ložys 2009). Gear costs and handling times were considered, but the additional costs involved in switching from gillnets to longlines, including bait (e.g., cost of bait, baiting hooks, and cleaning hooks; Berninsone et al. 2020) and training (Leathers and Leslie 2017) were not evaluated. After this case study was completed, commercial fishing for cod in most of the Baltic Sea was banned due to the decline in the eastern Baltic cod stock (Eero et al. 2015; ICES 2020). Vetemaa and Ložys (2009) also examined the potential to switch from gillnets to traps for the herring fishery that operates in the northern Baltic Sea. They did not include comparative seabird bycatch rates between the gear types but suggested that traps may be an effective alternative gear warranting further investigation based on the level of cooperation and acceptance of traps from the fishing community (Vetemaa and Ložys 2009).

Other research on gear-switching

The general concept of gear-switching as a strategy to meet fishery and conservation objectives has been previously considered. Königson et al. (2015) and Hedgärde et al. (2016) evaluated the use of pots to replace gillnets and longlines for the Baltic Sea cod fishery to reduce seal-inflicted damage to gear. Both studies demonstrated that pots were a viable alternative to the traditional gears for part of the fishing season. Information from these studies on how catches are affected by environmental and fisheries-related variables can be used to optimize gear-switching options (ICES 1997; Königson et al. 2015; Hedgärde et al. 2016).

In response to concerns about Māui dolphin (*Cephalorhynchus hectori maui*) bycatch in New Zealand gillnet and trawl fisheries, Leathers and Leslie (2017) reviewed longlines as alternative dolphin-safe gear. They noted that fishing industry leaders supported gear-switching proposals with some companies voluntarily phasing out gillnet and trawl gears and trialing alternative fishing methods in dolphin habitat. They also reported that many fishers emphasized the importance of government financial assistance for costs associated with gear-switching and fisher displacement. Estimates of costs to transition to longline gear, including changes in catch and revenue, retraining fishers, and upstream effects on businesses reliant on fisheries, were significant and posed a key challenge of minimizing short-term impacts to incentivize long-term sustainable bycatch mitigation (Leathers and Leslie 2017).

Another example of gear-switching to reduce bycatch of marine megafauna in gillnets was applied in Argentina. The franciscana dolphin (*Pontoporia blainvillei*) lives in coastal waters of southeastern South America and is considered threatened in Argentina due to removal of 3-5% of its population annually in artisanal gillnet fisheries (Berninsone et al. 2020). Several approaches to reduce gillnet bycatch focused on gear modifications were attempted. Acoustic deterrents (pingers) showed promise for reducing bycatch, but adoption of these devices was hampered by the costs of equipment and maintenance in the small-scale, multi-fleet coastal fishery. Time-area fishing restrictions were not considered to be a viable option to reduce dolphin bycatch because there was little support for monitoring and enforcement.

To address the conservation concerns, Berninsone et al. (2020) investigated the potential for gear-switching from gillnets to longlines. They compared bycatch and target catch rates between the gears with an economic analysis to determine potential fisher acceptance. They collaborated with fishers using both gear types over two years to monitor catch and bycatch in the same locations. Results indicated that target catch composition was similar for gillnets and longlines with reduced dolphin bycatch and less catch of juvenile fish in longlines. The authors concluded that switching from gillnets to longlines would effectively reduce bycatch of franciscana dolphins without increasing bycatch of other non-target species or reducing catch of target species. Seabird bycatch was also monitored, but no birds were reported in either gear over the course of the study. Economic analyses suggested that a complete switch from gillnets to longlines would reduce overall profitability and return on investment for the fishery. The increased costs associated with bait and additional labor for hooking and cleaning longlines compared to gillnets resulted in lower revenue for the fishers. The authors reported that 50% replacement of gillnets with longlines would be economically feasible over a five-year period, and dolphin bycatch could be significantly reduced with less than 100% gillnet replacement. Berninsone et al. (2020) suggested that a combination of gear-switching and gillnet gear modifications would minimize economic impacts and be more acceptable to traditional fishers.

In 2016, the ICES-FAO Working Group on Fish Technology and Fish Behavior convened a review of available information related to gear-switching to eliminate vaquita (*Phocoena sinus*) bycatch from gillnet fisheries in the Upper Gulf of California (ICES 2016). The vaquita, a small porpoise endemic to the Gulf of California, is a critically endangered species (Rojas-Bracho and Taylor 2017) that is threatened by gillnet bycatch (Jaramillo-Legorreta et al. 2007). Several gear alternatives that reduced bycatch were not effective in maintaining catch rates of target species, leading to rejection from fishers. A bottom-up social process that involved fishers was initiated to find alternative fishing gears, including small trawls that appear to maintain target catch while reducing bycatch (ICES 2016).

Gascoigne and Willsteed (2009) reviewed case studies of gear-switching in European fisheries and noted challenges related to the policy and regulatory environment, including inflexibility in the management system, gear conflicts, and target catch reduction. They highlighted the need to involve the fishing industry in decision-making, noting that small-scale fleets are often excluded from the process. They suggested that it may be appropriate to provide financial support for gear-switching options to reduce bycatch and habitat impacts but avoid subsidies that can lead to overcapacity. Reviews of gear-switching generally highlight the importance of including fishers in the decision-making processes to identify and optimize alternative gear selection, as well as the need for management and regulatory flexibility to ensure effective implementation.

Synthesis

The review of case studies evaluated performance of time-area restrictions and gear-switching for mitigating bycatch of seabirds in gillnet fisheries. None of the reviewed case studies reported information for all the performance criteria. The studies collectively offer general lessons on strengths and weaknesses of time-area fishing restrictions and gear-switching that can help guide future implementation (Table 1).

The review of time-area fishing restrictions suggests that this mitigation strategy can be effective to reduce seabird bycatch in gillnet fisheries. Time-area restrictions have been applied to a variety of fisheries issues globally (Alverson et al. 1994; Hall et al. 2000; Hall and Mainprize 2005) but remain controversial due to the potential to shift or increase bycatch in surrounding areas and to cause negative socioeconomic impacts on fishers (Gjertsen et al. 2010; Pascoe et al. 2010; Komoroske and Lewison 2015; Hazen et al. 2018). A large body of literature on potential use of time-area restrictions exists, but few studies have evaluated the success of closures to meet intended objectives. The reviewed case studies showed that time-area fishing restrictions have reduced gillnet bycatch of seabirds without impacting target and non-target catch and demonstrate strengths and weaknesses of the strategy (Table 1). Variations in spatial and temporal distributions of target and non-target species can cause a mismatch between management areas and high bycatch, as observed in the California coastal halibut fishery, where closure areas did not meet seabird bycatch reduction goals (Wild 1990). Alternatively, consideration of bycatch species behavior can help define fine-scale spatial and temporal measures that are effective, such as the seasonal and time-of-day restrictions applied in the Puget Sound salmon fishery (Melvin et al. 1999). Closures that are narrowly focused on reducing bycatch of a single species in one area have the potential to create new bycatch issues for multiple species by displaced fishing effort (Diamond et al. 2010; Northridge et al. 2017; Keith et al. 2020). For example, the Argentine hake closure resulted in increased bycatch of multiple seabird species and disrupted feeding ecology of pelagic seabirds (Copello et al. 2016). By contrast, the Canadian inshore cod and salmon moratoria resulted in population growth for diving seabirds (Regular et al. 2013). Large-scale fishery closures can lead to negative economic impacts, especially for artisanal coastal fishers that target local species by season and area and cannot access grounds far from their homeports (Batista et al. 2014; García-Flórez et al. 2014; Almeida et al. 2017). Alternatively, fine-scale fishing restrictions that focus on specific seasons and regions can be effective to reduce bycatch and provide benefits to coastal fisheries, including increased target catch rates, cost savings from cleaner fishing, and opportunities to participate in decision-making if bycatch patterns are predictable (Gell and Roberts 2002; Bellebaum et al. 2013; Benbow et al. 2014; Baerum et al. 2019; Barz et al. 2020).

Despite few direct comparisons of seabird bycatch reduction between gillnets and alternative gears, the potential for meeting conservation objectives through gear-switching is promising, with some further development needed for successful application (Table 1). Case studies of gear-switching to reduce seabird bycatch in gillnet fisheries on the US west coast and in the Baltic Sea showed encouraging performance of the alternative gears in maintaining target catch levels without increasing bycatch of non-target species. The switch to otter trawls in the California halibut fishery effectively reduced seabird bycatch to meet conservation objectives (Haseltine and Thornton 1990), and the experimental longline switch in the Baltic cod fishery did not reduce target species catch (Vetemaa and Ložys 2009). In both cases, however, the alternative fishing gears were more efficient at capturing target species, creating unanticipated challenges for implementation. Increased catch efficiency can result in economic benefits for some fishers, but possibly at the expense of others that are limited by vessel characteristics, geographic scope, or competing operations (Haseltine and Thornton 1990; Hall et al. 2000). Furthermore, increased fishing efficiency can

Table 1. Strengths and weaknesses of time-area fishing restrictions and gear-switching to reduce seabird bycatch in gillnet fisheries.

	Time-Area Restrictions		Gear-Switching	
Evaluation Criterion	Strengths	Weaknesses	Strengths	Weaknesses
Bycatch Reduction	• Effective when overlap of fishing and bycatch occurs • Potential to monitor long-term effects • Can match bycatch targets with spatial and temporal restrictions • Prediction tools can evaluate effectiveness prior to implementation	• Potential to shift bycatch spatially or temporally • Few post-implementation evaluations • Requires understanding of variations in bycatch species distribution and behaviors • Uncertainty in predictions associated with data gaps	• Effective if alternative gears have lower bycatch • Ability to set bycatch reduction targets based on observed bycatch rates by gear type	• Requires extensive experimental testing • Rare bycatch events can impair effectiveness and testing • Potential to increase bycatch in specific times or areas
Target Catch	• Fine-scale and dynamic approaches can be tailored to maintain catch • Potential to shift target species to increase profit • Allows fulfillment of target quota seasonally or spatially	• May restrict ability to target some species • Possible reduction in catch rates or impacts on other fisheries in areas of displacement • Potential impacts to quota fulfillment	• Alternative gears can have similar catch rates • Can maintain target species catch composition	• Possible reduction in target catch levels • New limits on catch or effort may be needed • May change catch composition to different sizes of target catch or different target species
Non-Target Catch	• Can be designed to minimize impacts • Potential to increase landings of managed species outside closures	• New bycatch impacts in times or areas with displaced fishing effort	• Can be regulated to minimize impacts • Alternative gears can expand targeting of underutilized species	• New bycatch impacts from different gear types • Requires extensive experimental testing
Implementation	• Adaptable to meet multiple objectives • Enforceable with adequate monitoring and administrative capacity • Ability to incentivize innovative or holistic approaches	• Defining scale is data-dependent • Adequate monitoring and enforcement needed • Potential to reduce fishery economic viability and displace participants	• Fisher input to identify appropriate alternatives • May reduce economic impacts compared to other strategies • Ability to incentivize innovative or holistic approaches	• Lack of incentive to change fishing practices • Increased costs of gear replacement, training, and handling time • Potential to reduce fishery economic viability and displace participants

result in depletion of target species and increased administrative demands for regulation, monitoring, and enforcement (Vetemaa and Ložys 2009; Murawski 2010). It may be possible to overcome such challenges with broad acceptance from fishers about the benefits of gear-switching, as noted in the herring pot fishery example (Vetemaa and Ložys 2009).

In addition to evaluating bycatch reduction and target catch criteria, the potential for effective implementation of time-area restrictions and gear-switching was examined. Some of the experimental time-area measures tested in both the Puget Sound salmon fishery and California halibut fishery were applied as regulations on the entire fleet and successfully reduced seabird bycatch in the long-term (e.g., WA DFW 2020 and Forney et al. 2001, respectively). Cost analyses of gear-switching to reduce bycatch of dolphins in Argentinian artisanal fisheries suggest fisher acceptance over the long-term (Berninsone et al. 2020), and several fishing companies in New Zealand have been willing to voluntarily switch gears to reduce dolphin bycatch (Leathers and Leslie 2017).

Monitoring and enforcement are key elements to ensure time-area fishing restrictions are successful, and incentives and costs are critical components to consider when developing gear-switching strategies (Grafton et al. 2006; Eayrs et al. 2015). Barz et al. (2020) studied fisher characteristics to predict potential acceptance of seabird bycatch mitigation measures for gillnet fisheries. Through a series of interviews and expert workshops, fishers were categorized in three main types, including those who anticipate future developments and innovate solutions, those who are focused on present conditions and operate opportunistically, and those who are past-oriented with reluctance to adapt to changing situations (Barz et al. 2020). The authors correlated these fisher characteristics with bycatch mitigation options, including time-area fishing restrictions and gear-switching, and suggested that acceptance of bycatch reduction tools may be dependent on the level of participation of each fisher type in a region. They noted that fishers who are likely to innovate could collaborate with scientists and managers to develop novel bycatch mitigation approaches, whereas fishers that are reluctant to change may need additional incentives to accept bycatch reduction measures. The authors suggested that education programs aimed at changing the discourse about impacts of seabird bycatch can raise awareness of conservation concerns, and that cooperative agreements between government agencies and fishing organizations would facilitate acceptance of mitigation measures. Quantifying the relative proportions of each fisher type can be useful to prioritize management options. For example, if a high percentage of a fleet is comprised of innovative fishers that will implement effective bycatch reduction measures, it may not be necessary to mandate measures across the entire fleet to meet conservation objectives (Barz et al. 2020). Understanding the motivations, local ecological knowledge, individual skills, and cultural background of fishers can help to develop effective bycatch mitigation strategies (Grafton et al. 2006; Barz et al. 2020).

Discussion

Seabird bycatch in gillnet fisheries remains a considerable source of mortality that impacts several threatened species. A holistic approach to reduce seabird bycatch in gillnets, including understanding of seabird biology, habitat preference, and feeding ecology combined with information about fishing activity, target species, and socioeconomic impacts, may provide a framework to develop mitigation measures. Combining measures (e.g., time-area fishing restrictions and gear-switching) may be feasible in certain regions, if fine-scale spatial and temporal information about the overlap of seabirds and gillnet gear is available. Although time-area restrictions and gear-switching may impact the ability of fishers to operate in traditional ways, these management procedures may incentivize innovative solutions that can be applied to minimize impacts on fishing activities while meeting seabird conservation objectives.

An iterative approach that refines specific tools and builds upon lessons learned from success and failure of various methods is needed to meet conservation and fishery objectives for coastal gillnet activities. Considering a variety of predictive tools to project potential outcomes may be a necessary first step for development of seabird bycatch reduction programs. The emerging concept of dynamic ocean management, which applies information to manage on discrete spatial and temporal scales (Lewison et al. 2015; Maxwell et al. 2015; Hazen et al. 2018; Zhou et al. 2019), may provide useful examples to apply to coastal gillnet fisheries. Fine-scale time-area fishing restrictions have not been extensively evaluated for effectiveness in reducing seabird bycatch in gillnet fisheries, but this approach may be effective in regions where seasonal and spatial distribution patterns of seabirds and gillnet activity have been documented (Sonntag et al. 2012; Bellebaum et al. 2013; Almeida et al. 2017; Baerum et al. 2019; Glemarec et al. 2020). The effects of climate change on fish and seabird distribution also need to be considered when designing time-area restrictions, and flexibility to adapt closure areas could be considered in the implementation phase. Additionally, fine-scale time-area restrictions may allow for more rapid implementation of bycatch reduction measures than large closures to meet conservation directives. Restricting gillnet use in areas and seasons of high seabird abundance may reduce bycatch while allowing continued fishing activity, but input from fishers is required to develop acceptable time-area measures.

Developing metrics based on specific goals for bycatch and target species to assess whether gear-switching is suitable for a fishery could be useful in identifying alternative gears, areas, and seasons for implementation (Willison and Côte 2009). Such metrics (e.g., maximum cost to fishers, bycatch thresholds, and administrative capacity) are essential to consider for small-scale coastal gillnet fisheries where fishing operations are limited by season, geography, vessel characteristics, target species, and economic factors. The impacts of a gillnet ban in Florida offer lessons in unintended consequences. Gear-switching resulted in overfishing of an alternative target species, displacement of fishers that suffered from reduced income and mental health issues, and negative impacts on food security (Shivlani et al. 1998; Smith et al. 2003; Loring 2017). These types of negative consequences can be avoided when gear-switching options are developed collaboratively with fishers and a balance of costs and benefits are considered. Incentives for gear-switching include subsidies and buyback programs for gear replacement, training and education for alternative gears, recognition of adoption of alternative gears, and flexibility in management to facilitate long-term sustainable benefits (Fulton and Smith 2007; McClanahan et al. 2009; Jenkins and Garrison 2013; Eayrs et al. 2015; Loring 2017; Barz et al. 2020).

Defining bycatch reduction goals can be challenging because they depend on societal objectives, regulatory mandates, population status, economic tradeoffs, and data availability. Consideration of bycatch impacts at the population scale is necessary to identify reduction targets that weigh conservation goals against fishery costs (Northridge et al. 2017; ICES 2018). Applying consistent criteria across multiple taxa (e.g., marine mammals, turtles, and seabirds) can ensure that mitigation strategies do not simply shift bycatch from one species to another (Moore et al. 2009). Seabird bycatch may be viewed as a component of accepted daily fishing activity by fishers (Barz et al. 2020), which requires a change in attitude through discourse as a needed initial step to develop successful mitigation strategies. Characterizing patterns in fisher motivations and incentives may also allow management actions to focus on the most realistic approaches to reduce bycatch, such as cooperative agreements and adaptive management for fine-scale fishing restrictions or gear-switching (Barz et al. 2020). Additionally, an evaluation of monitoring and enforcement requirements to determine availability of existing infrastructure and identify gaps in administrative systems would help to define realistic objectives and ensure effective implementation.

Successful mitigation strategies typically result from tailoring solutions to specific bycatch problems and addressing challenges holistically. Modifying fishing gear can be an acceptable bycatch mitigation approach for fishers because it does not prohibit or substantially change fishing activities. By contrast, time-area restrictions and gear-switching have greater impacts on fishing behavior. Additional research is needed to develop gear modifications that meet seabird bycatch reduction goals, which could be combined with time-area fishing restrictions and gear-switching to reach conservation objectives. Although these measures may be successful for reducing bycatch in some areas, they may also cause economic difficulties for fishers, which pose challenges to implementation, enforcement, and compliance. Consideration of fisher perspectives and incentives is critical for establishing realistic and measurable bycatch reduction targets, incentivizing uptake of mitigation measures, maintaining long-term sustainability, and achieving conservation goals. Integrated regionally specific information on seasonal seabird habitat use, fishing effort, target species, and fisher incentives, combined with established and measurable bycatch reduction goals will allow for development of effective management strategies to reduce seabird bycatch in gillnet fisheries.

Acknowledgements

Thanks to the participants of the 2021 International Gillnet Bycatch Workshop, organized by The Royal Society for the Protection of Birds and BirdLife International, and supported by The David and Lucille Packard Foundation, for providing feedback on the review.

Funding

This work was funded by The Royal Society for the Protection of Birds and BirdLife International.

ORCID

Catherine E. O'Keefe http://orcid.org/0000-0002-5667-0869
Steven X. Cadrin http://orcid.org/0000-0003-0787-677X
Gildas Glemarec http://orcid.org/0000-0003-1801-3179
Yann Rouxel http://orcid.org/0000-0002-0619-6580

References

Abbott JK, Wilen JE. 2009. Regulation of fisheries bycatch with common-pool output quotas. J Environ Econ Manag. 57(2):195–204. doi:10.1016/j.jeem.2008.04.003

Allison EH, Ellis F. 2001. The livelihoods approach and management of small-scale fisheries. Mar Policy. 25(5):377–388. doi:10.1016/S0308-597X(01)00023-9

Almeida A, Ameryk A, Campos B, Crawford R, Krogulec J, Linkowski T, Mitchell R, Mitchell W, Oliveira N, Oppel S, et al. 2017. Study on Mitigation Measures to Minimize Seabird Bycatch in Gillnet Fisheries. European Commission Service Contract No: EASME/EMFF/2015/1.3.2.1/SI2.719535.

Alverson DL, Freeberg MH, Pope JG, Murawski SA. 1994. A global assessment of fisheries bycatch and discards. Rome (IT): FAO Fisheries Technical Paper No: 339.

Anderson ORJ, Small CL, Croxall JP, Dunn EK, Sullivan BJ, Yates O, Black A. 2011. Global seabird bycatch in longline fisheries. Endang Species Res. 14(2):91–106. doi:10.3354/esr00347

Baerum KM, Anker-Nilssen T, Christensen-Dalsgaard S, Fangel K, Williams T, Volstad JH. 2019. Spatial and temporal variations in seabird bycatch: Incidental bycatch in the Norwegian coastal gillnet-fishery. PLoS One. 14(3):e0212786. doi:10.1371/journal.pone.0212786

Barz F, Eckardt J, Meyer S, Kraak SBM, Strehlow HV. 2020. Boats don't fish, people do' – how fishers' agency can inform fisheries-management on bycatch mitigation of marine mammals and sea birds. Mar Policy. 122:104268. doi:10.1016/j.marpol.2020.104268

Bastardie F, Brown EJ, Andonegi E, Arthur R, Beukhof E, Depestele J, Döring R, Eigaard OR, García-Barón I, Llope M, et al. 2021. A review characterizing 25 ecosystem challenges to be addressed by an ecosystem approach to fisheries management in Europe. Front Mar Sci. 7:629186.

Batista VS, Fabre NN, Malhado ACM, Ladle RJ. 2014. Tropical artisanal fisheries: challenges and future directions. Rev Fish Sci Aquac. 22(1):1–15. doi:10.1080/10641262.2013.822463

Bellebaum J, Schirmeister B, Sonntag N, Garthe S. 2013. Decreasing but still high: bycatch of seabirds in gillnet

fisheries along the German Baltic coast. Aquatic Conserv: Mar Freshw Ecosyst. 23(2):210–221. doi:10.1002/aqc.2285
Benbow S, Humber F, Oliver TA, Oleson KLL, Raberinary D, Nadon M, Ratsimbazafy H, Harris A. 2014. Lessons learnt from experimental temporary octopus fishing closures in south-west Madagascar: benefits of concurrent closures. Afr J Mar Sci. 36(1):31–37. doi:10.2989/1814232X.2014.893256
Benjamins S, Kulka D, Lawson J. 2008. Incidental catch of seabirds in Newfoundland and Labrador gillnet fisheries, 2001–2003. Endang Species Res. 5:149–160. doi:10.3354/esr00094
Bentzen R, Robards MD. 2014. Review of seabird bycatch in set-gillnets with specific reference to mitigating impacts to yellow-billed loons. Wildlife Conservation Society. p. 35. https://library.wcs.org/doi/ctl/view/mid/33065/pubid/DMX2983500000.aspx.
Berninsone LG, Bordino P, Gnecco M, Foutel M, Mackay AI, Werner TB. 2020. Switching gillnets to longlines: an alternative to mitigate the bycatch of franciscana dolphins (Pontoporia blainvillei) in Argentina. Front Mar Sci. 7:699.
Bethoney ND, Schondelmeier BP, Stokesbury KDE, Hoffman WS. 2013a. Developing a fine scale system to address river herring (Alosa pseudoharengus, A. aestivalis) and American shad (A. sapidissima) bycatch in the U.S. Northwest Atlantic mid-water trawl fishery. Fish Res. 141:79–87. doi:10.1016/j.fishres.2012.09.003
Bethoney ND, Stokesbury KDE, Cadrin SX. 2013b. Environmental links to alosine at-sea distribution and bycatch in the northwest Atlantic mid-water trawl fishery. ICES J Mar Sci. 71(5):1246–1255. doi:10.1093/icesjms/fst013
Bisack KD, Sutinen JG. 2006. Harbour Porpoise Bycatch: ITQs or Time/Area Closures in the New England Gillnet Fishery. Land Econ. 82(1):85–102. doi:10.3368/le.82.1.85
Broeg K. 2007. Towards low impact fishery techniques. World Wildlife Federation Germany, International Centre for Marine Conservation. Hamburg, Germany. http://charlie-gibbs.org/charlie/NEA_Website/Projects/Reports/WWF_Low_Impact_Fisheries_Report.pdf.
Bull LS. 2007. Reducing seabird bycatch in longline, trawl and gillnet fisheries. Fish Fisheries.Fisheries 8(1):31–56. doi:10.1111/j.1467-2979.2007.00234.x
Bull LS. 2009. New mitigation measures reducing seabird by-catch in trawl fisheries. Fish Fish. 10(4):408–427. doi:10.1111/j.1467-2979.2009.00327.x
California Ocean Science Trust (CA OST). 2013. Rapid assessments for selected California fisheries. Oakland, CA USA. August 2013. https://opc.ca.gov/webmaster/ftp/project_pages/Rapid%20Assessments/CA%20Rapid%20Assessments.pdf.
Cantlay JC, Bond AL, Wells-Berlin AM, Crawford R, Martin GR, Rouxel Y, Peregoy S, McGrew KA, Portugal SJ. 2020. Ineffectiveness of light emitting diodes as underwater deterrents for Long-tailed Ducks Clangula hyemalis. Glob Ecol Conserv. 23:e01102. doi:10.1016/j.gecco.2020.e01102
Carneiro APB, Pearmain EJ, Oppel S, Clay TA, Phillips RA, Bonnet-Lebrun A-S, Wanless RM, Abraham E, Richard Y, Rice J, et al. 2020. A framework for mapping the distribution of seabirds by integrating tracking, demography and phenology. J Appl Ecol. 57(3):514–525. doi:10.1111/1365-2664.13568
Christensen-Dalsgaard S, Anker-Nilssen T, Crawford R, Bond A, Sigurðsson GM, Glemarec G, Hansen ES, Kadin M, Kindt-Larsen L, Mallory M, et al. 2019. What's the catch with lumpsuckers? A North Atlantic study of seabird bycatch in lumpsucker gillnet fisheries. Biol Conserv. 240:108278. doi:10.1016/j.biocon.2019.108278
Chuenpagdee R, Morgan LE, Maxwell SM, Norse EA, Pauly D. 2003. Shifting gears: assessing collateral impacts of fishing methods in US waters. Front Ecol Environ. 1(10):517–524. doi:10.1890/1540-9295(2003)001[0517:SGACIO2.0.CO;2]
Clay TA, Small C, Tuck GN, Pardo D, Carneiro APB, Wood AG, Croxall JP, Crossin GT, Phillips RA. 2019. A comprehensive large-scale assessment of fisheries bycatch risk to threatened seabird populations. J Appl Ecol. 56(8):1882–1893. doi:10.1111/1365-2664.13407
Copello S, Blanco GS, Seco Pon JP, Quintana F, Favero M. 2016. Exporting the problem: Issues with fishing closures in seabird conservation. Mar Policy. 74:120–127. doi:10.1016/j.marpol.2016.09.008
Crawford R, Ellenberg U, Frere E, Hagen C, Baird K, Brewin P, Crofts S, Glass J, Mattern T, Pompert J, et al. 2017. Tangled and drowned: a global review of penguin bycatch in fisheries. Endang Species Res. 34:373–396. doi:10.3354/esr00869
Crowder LB, Murawski SA. 1998. Fisheries bycatch: implications for management. Fisheries 23(6):8–17. doi:10.1577/1548-8446(1998)023<0008:FBIFM > 2.0.CO;2
Croxall JP, Butchart SHM, Lascelles B, Stattersfield AJ, Sullivan B, Symes A, Taylor P. 2012. Seabird conservation status, threats and priority actions: a global assessment. Bird Conserv Int. 22(1):1–34. doi:10.1017/S0959270912000020
Croxall JP. 2008. The role of science and advocacy in the conservation of Southern Ocean albatrosses at sea. Bird Conserv Int. 18(S1):S13–S29. doi:10.1017/S0959270908000300
Dawson SM, Northridge S, Waples D, Read AJ. 2013. To ping or not to ping: the use of active acoustic devices in mitigating interactions between small cetaceans and gillnet fisheries. Endang Species Res. 19(3):201–221. doi:10.3354/esr00464
Diamond SL, Kleisner KM, Duursma DE, Wang Y. 2010. Designing marine reserves to reduce bycatch of mobile species: a case study using juvenile red snapper (Lutjanus campechanus). Can J Fish Aquat Sci. 67(8):1335–1349. doi:10.1139/F10-044
Dias MP, Martin R, Pearmain EJ, Burfield IJ, Small C, Phillips RA, Yates O, Lascelles B, Borboroglu PG, Croxall JP. 2019. Threats to seabirds: A global assessment. Biol Conserv. 237:525–537. doi:10.1016/j.biocon.2019.06.033
Dunn DC, Boustany AM, Halpin PN. 2011. Spatio-temporal management of fisheries to reduce by-catch and increase fishing selectivity. Fish Fish. 12(1):110–119. doi:10.1111/j.1467-2979.2010.00388.x
Durant JM, Hjermann DO, Frederiksen M, Charrassin JB, Le Maho Y, Sabarros PS, Crawford RJM, Stenseth NC. 2009. Pros and cons of using seabirds as ecological indicators. Clim Res. 39(2):115–129. doi:10.3354/cr00798
Eayrs S, Cadrin SX, Glass CW. 2015. Managing change in fisheries: a missing key to fishery-dependent data collec-

tion? ICES J Mar Sci. 72(4):1152–1158. doi:10.1093/icesjms/fsu184

Eero M, Hjelm J, Behrens J, Buchmann K, Cardinale M, Casini M, Gasyukov P, Holmgren N, Horbowy J, Hüssy K, et al. 2015. Eastern Baltic cod in distress: biological changes and challenges for stock assessment. ICES J Mar Sci. 72(8):2180–2186. doi:10.1093/icesjms/fsv109

European Commission (EC). 2017. Commission Decision (EU) 2017/848 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardized methods for monitoring and assessment, and repealing Decision 2010/477/EU. Off J Euro Union L 125:43–73.

Exeter OM, Htut T, Kerry CR, Kyi MM, Mizrahi M, Turner RA, Witt MJ, Bicknel AWJ. 2021. Shining light on data-poor coastal fisheries. Front Mar Sci. 7:625766.

Field R, Crawford R, Enever R, Linkowski T, Martin G, Morkūnas J, Morkūnė R, Rouxel Y, Oppel S. 2019. High contrast panels and lights do not reduce bird bycatch in Baltic Sea gillnet fisheries. Glob Ecol Conserv. 18:e00602. doi:10.1016/j.gecco.2019.e00602

Food and Agriculture Organization (FAO). 2010. Report of the FAO/unep expert meeting on impacts of destructive fishing practices, unsustainable fishing, and illegal, unreported and unregulated (IUU) fishing on marine biodiversity and habitats, Rome. 23–25 September 2009. FAO Fisheries and Aquaculture Report No. 932 FIRF/R932.

Food and Agriculture Organization (FAO). 2021. Fishing operations. Guidelines to prevent and reduce bycatch of marine mammals in capture fisheries. Rome: FAO Technical Guidelines for Responsible Fisheries . doi:10.4060/cb2887en

Forney KA, Benson SR, Cameron GA. 2001. Central California gillnet effort and bycatch of sensitive species, 1990-1998. Proceedings of Seabird Bycatch: Trends, Roadblocks, and Solutions. University of Alaska Sea Grant. AK-SG-01-01. https://swfsc-publications.fisheries.noaa.gov/publications/CR/2001/2001For.pdf.

Frimodig A, Horeczko M, Mason T, Owens B, Prall M, Tillman T, Wertz T. 2008. Review of California Halibut Trawl Fishery in the California Halibut Trawl Grounds. Report to the California Fish and Game Commission, State Fisheries Evaluation Project (06/27/2008). p. 43

Fulton EA, Smith ADM. 2007. Alternative Management Strategies for Southeast Australian Commonwealth Fisheries: Stage 2: Quantitative Management Strategy Evaluation. Australian Fisheries Management Authority Fisheries Research and Development Corporation. p. 405. https://research.csiro.au/atlantis/wp-content/uploads/sites/52/2015/10/AMS_Final_Report_v6.pdf.

García-Flórez L, Morales J, Gaspar MB, Castilla D, Mugerza E, Berthou P, García de la Fuente L, Oliveira M, Moreno O, García del Hoyo JJ, et al. 2014. A novel and simple approach to define artisanal fisheries in Europe. Mar Policy. 44:152–159. doi:10.1016/j.marpol.2013.08.021

Gascoigne J, Willsteed E. 2009. Moving towards low impact fisheries in Europe, policy hurdles & actions. Seas at Risk. p. 103. pp. https://seas-at-risk.org/images/pdf/archive/SAR_LIF.pdf.

Gell FR, Roberts CM. 2002. The fishery effects of marine reserves and fishery closures. Washington DC (USA): WWF-US.

Gilman EL, Dalzell P, Martin S. 2006. Fleet communication to abate fisheries bycatch. Mar Policy.30(4):360–366. doi:10.1016/j.marpol.2005.06.003

Gjertsen H, Hall M, Squires D. 2010. Incentives to address bycatch issues In: Allen R, Joseph JA, Squires D, editors. Conservation and management of transnational tuna fisheries. Oxford (UK): Wiley-Blackwell. p. 225–248.

Glemarec G, Kindt-Larsen L, Scherffenberg Lundgaard L, Larsen F. 2020. Assessing Seabird Bycatch in Gillnet Fisheries Using Electronic Monitoring. Biol Conserv. 243:108461. doi:10.1016/j.biocon.2020.108461

González-Zevallos D, Yorio P. 2006. Seabird use of discards and incidental captures at the Argentine hake trawl fishery in the Golfo San Jorge, Argentina. Mar Ecol Prog Ser. 316:175–183. doi:10.3354/meps316175

Grafton RQ, Arnason R, Bjørndal T, Campbell D, Campbell HF, Clark CW, Connor R, Dupont DP, Hannesson R, Hilborn R, et al. 2006. Incentive-based approaches to sustainable fisheries. Can J Fish Aquat Sci. 63(3):699–710. doi:10.1139/f05-247

Hall MA, Alverson DL, Metuzals KI. 2000. Bycatch: problems and solutions. Mar Pollut Bull. 41(1-6):204–219. doi:10.1016/S0025-326X(00)00111-9

Hall MA. 1998. An ecological view of the tuna-dolphin problem: impacts and trade-offs. Rev Fish Biol Fish. 8(1):1–34. doi:10.1023/A:1008854816580

Hall SJ, Mainprize BM. 2005. Managing by-catch and discards: how much progress are making and how can we do better? Fish Fish. 6(2):134–155. doi:10.1111/j.1467-2979.2005.00183.x

Hamilton S, Baker GB. 2019. Technical mitigation to reduce marine mammal bycatch and entanglement in commercial fishing gear: lessons learnt and future directions. Rev Fish Biol Fish. 29(2):223–247. doi:10.1007/s11160-019-09550-6

Hanamseth R, Baker GB, Sherwen S, Hindell M, Lea MA. 2017. Assessing the importance of net color as a seabird bycatch mitigation measure in gillnet fishing. Aquat Conserv. 2017:1–7.

Haseltine AW, Thornton S. 1990. Alternative gear development off central California In: Haugen CW, editor. The California halibut, Paralichthys californicus, resource and fisheries. San Diego (CA): California Department of Fish and Game. Fish Bulletin 174. p. 341–358.

Hazen EL, Scales KL, Maxwell SM, Briscoe DK, Welch H, Bograd SJ, Bailey H, Benson SR, Eguchi T, Dewar H, et al. 2018. A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. Sci Adv. 4(5):eaar3001. doi:10.1126/sciadv.aar3001

Hedgärde M, Berg CW, Kindt-Larsen L, Lunneryd SG, Königson S. 2016. Explaining the catch efficiency of different cod pots using underwater video to observe cod entry and exit behavior. J Ocean Technol. 11:67–90.

Hobday AJ, Hartman K. 2006. Near real-time spatial management based on habitat predictions for a longline bycatch species. Fish. Manag. 13(6):365–380. doi:10.1111/j.1365-2400.2006.00515.x

Holland DS, Martin C. 2019. Bycatch quotas, risk pools, and cooperation in the Pacific whiting fishery. Front Mar Sci. 6:1–9.

ICES 2016. Report of the Working Group on Fishing Technology and Fish Behavior (WGFTFB). Merida, Mexico. ICES CM 2016/SSGIEOM:22. p. 183.

ICES. 1997. Report of the Working Group on Fishing Technology and Fish Behavior (WGFTFB). Hamburg, Germany. http://www.ices.dk/sites/pub/CM%20Doccuments/1997/B/B0297.pdf.

ICES. 2018. JWGBIRD Report 2018: report of the joint OSPAR/HELCOM/ICES working group on marine birds (JWGBIRD). ICES CM 2017/ACOM:24. p.79

ICES. 2020. Cod (Gadus morhua) in subdivisions 24-32, eastern Baltic stock (eastern Baltic Sea). ICES Advice on fishing opportunities, catch, and effort. Cod.27.24-32. https://www.ices.dk/sites/pub/Publication%20Reports/Advice/2020/2020/cod.27.24-32.pdf.

Jaramillo-Legorreta A, Rojas-Bracho L, Brownell RL, Jr, Read AJ, Reeves RR, Ralls K, Taylor BL. 2007. Saving the vaquita: immediate action, not more data. Conserv Biol. 21:1653–1655.

Jenkins LD, Garrison K. 2013. Fishing gear substitution to reduce bycatch and habitat impacts: An example of social–ecological research to inform policy. Mar Policy. 38:293–303. doi:10.1016/j.marpol.2012.06.005

Keith DM, Sameoto JA, Keyser FM, Ward-Paige CA. 2020. Evaluating socio-economic and conservation impacts of management: A case study of time-area closures on Georges Bank. PLoS One. 15(10):e0240322.

King WB, Brown RGB, Sanger GA. 1979. Mortality to marine birds through commercial fishing In: Bartonek JC, Nettleship DN, editors. Conservation of Marine Birds of Northern North America Washington DC: US Fish and Wildlife Service, Wildlife Research Report 11. p. 195–200.

Kirby DS, Ward P. 2014. Standards for the effective management of fisheries bycatch. Mar Policy. 44:419–426. doi:10.1016/j.marpol.2013.10.008

Komoroske LM, Lewison RL. 2015. Addressing fisheries bycatch in a changing world. Front Mar Sci. 2:83.

Königson SJ, Fredriksson RE, Lunneryd S-G, Strömberg P, Bergström UM. 2015. Cod pots in a Baltic fishery: are they efficient and what affects their efficiency? ICES J Mar Sci 75:1545–1554.

Leathers A, Leslie A. 2017. Gear switching to remove threats to Māui dolphin and address the socio-economic barriers to effective conservation. International Whaling Commission Paper SC/67A/HIM/12.

Lewison R, Crowder LB, Wallace BP, Moore JE, Cox T, Žydelis R, McDonald S, DiMatteo A, Dunn DC, Kot CY, et al. 2014. Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. Proc Natl Acad Sci U S A. 111(14):5271–5276.

Lewison R, Hobday AJ, Maxwell S, Hazen E, Hartog JR, Dunn DC, Briscoe D, Fossette S, O'Keefe CE, Barnes M, et al. 2015. Dynamic Ocean Management: 21st century approaches for marine resource management and conservation. Bioscience. 65(5):486–498. doi:10.1093/biosci/biv018

Lewison RL, Crowder LB, Read AJ, Freeman SA. 2004. Understanding impacts of fisheries bycatch on marine megafauna. Trends Ecol Evol. 19(11):598–604. doi:10.1016/j.tree.2004.09.004

Lewison RL, Nel D, Taylor F, Croxall JP, Rivera K. 2005. Thinking big – taking a largescale approach to seabird bycatch. Mar Ornithol. 33:1–5.

Lewison RL, Soykan CU, Cox T, Peckham H, Pilcher N, LeBoeuf N, McDonald S, Moore J, Safina C, Crowder LB. 2011. Ingredients for addressing the challenges of fisheries bycatch. BMS 87(2):235–250. doi:10.5343/bms.2010.1062

Løkkeborg S. 2011. Best practices to mitigate seabird bycatch in longline, trawl and gillnet fisheries – efficiency and practical applicability. Mar Ecol Prog Ser. 435:285–303. doi:10.3354/meps09227

Loring PA. 2017. The political ecology of gear bans in two fisheries: Florida's net ban and Alaska's Salmon wars. Fish Fish. 18(1):94–104. doi:10.1111/faf.12169

Lowman B, O'Keefe CE, Cadrin SX. 2021. Predictive models of yellowtail flounder bycatch in the U.S. sea scallop fishery on Georges Bank. J Northwest Atl Fish Sci. 52:1–18.

Mangel JC, Wang J, Alfaro-Shigueto J, Pingo S, Jimenez A, Carvalho F, Swimmer T, Godley BJ. 2018. Illuminating gillnets to save seabirds and the potential for multi-taxa bycatch mitigation. R Soc Open Sci. 5(7):180254.

Marchowski D, Jankowiak Ł, Ławicki Ł, Wysocki D, Chylarecki P. 2020. Fishery bycatch is among the most important threats to the European population of Greater Scaup Aythya marila. Bird Conserv Int. 30(2):176–193. doi:10.1017/S0959270919000492

Martin GR, Crawford R. 2015. Reducing bycatch in gillnets: A sensory ecology perspective. Glob Ecol Conserv. 3:28–50. doi:10.1016/j.gecco.2014.11.004

Maxwell SM, Hazen EL, Lewison RL, Dunn DC, Bailey H, Bograd SJ, Briscoe DK, Fossette S, Hobday AJ, Bennett M, et al. 2015. Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. Mar Policy. 58:42–50. doi:10.1016/j.marpol.2015.03.014

McClanahan TR, Castilla JC, White AT, Defeo O. 2009. Healing small-scale fisheries by facilitating complex socio-ecological systems. Rev Fish Biol Fish. 19(1):33–47. doi:10.1007/s11160-008-9088-8

Melvin EF, Parrish JK, Conquest LL. 1999. Novel tools to reduce seabird bycatch in coastal gillnet fisheries In: Melvin EF, Parrish JK, editors. Seabird Bycatch: Trends, Roadblocks, and Solutions. Fairbanks (AK): University of Alaska Sea Grant AK-SG-01-01. p. 161–190.

Merkel FR. 2011. Gillnet bycatch of seabirds in Southwest Greenland, 2003 - 2008. Technical Report No. 85, Pinngortitaleriffik, Greenland Institute of Natural Resources. http://old.naturgl.lfac.dk/fileadmin/user_files/Dokumenter/Tekniske_rapporter/GN_TR_85_Seabird-Bycatch_Merkel__2011.pdf.

Moore JE, Wallace BP, Lewison RL, Žydelis R, Cox TM, Crowder LB. 2009. A review of marine mammal, sea turtle and seabird bycatch in USA fisheries and the role of policy in shaping management. Marine Pol. 33(3):435–451. doi:10.1016/j.marpol.2008.09.003

Murawski SA. 2010. Rebuilding depleted fish stocks: the good, the bad, and mostly, the ugly. ICES J Mar Sci. 67(9):1830–1840. doi:10.1093/icesjms/fsq125

Murray KT, Read AJ, Solow AR. 2000. The use of time/area closures to reduce bycatches of harbour porpoises: lessons from the Gulf of Maine sink gillnet fishery. J Cetacean Res Manag. 2:135–141.

Myers RA, Hutchings JA, Barrowman NJ. 1997. Why do fish stocks collapse? The example of cod in Atlantic Canada. Ecol Appl. 7(1):91–106. doi:10.1890/1051-0761(1997)007[0091:WDFSCT2.0.CO;2]

Northridge S, Coram A, Kingston A, Crawford R. 2017. Disentangling the causes of protected-species bycatch in gillnet fisheries. Conserv Biol. 31(3):686–695. doi:10.1111/cobi.12741

O'Keefe CE, Cadrin SX, Stokesbury KDE. 2014. Evaluating effectiveness of time/area closures, quotas/caps and fleet communications to reduce fisheries bycatch. ICES J Mar Sci. 71(5):1286–1297. doi:10.1093/icesjms/fst063

O'Keefe CE, DeCelles GR. 2013. Forming a partnership to avoid bycatch. Fisheries 38(10):434–444. doi:10.1080/03632415.2013.838122

Orben RA, Adams J, Hester M, Shaffer SA, Suryan RM, Deguchi T, Ozaki K, Sato F, Young LC, Clatterbuck C, et al. 2021. Across borders: External factors and prior behavior influence North Pacific albatross associations with fishing vessels. J Appl Ecol. 58(6):1272–1212. doi:10.1111/1365-2664.13849

Orphanides CD, Palka DL. 2013. Analysis of harbour porpoise gillnet bycatch, compliance, and enforcement trends in the US northwestern Atlantic, January 1999 to May 2010. Endang Species Res. 20(3):251–269. doi:10.3354/esr00499

Österblom H, Fransson H, Olsson O. 2002. Bycatches of common guillemot (Uria aalge) in the Baltic Sea gillnet fishery. Biol Conserv. 105(3):309–319. doi:10.1016/S0006-3207(01)00211-7

Pace RII, Cole TVN, Henry AG. 2014. Incremental fishing gear modifications fail to significantly reduce large whale series injury rates. Endang Species Res. 26(2):115–126. doi:10.3354/esr00635

Parsons M, Mitchell I, Butler A, Ratcliffe N, Frederiksen M, Foster S, Reid JB. 2008. Seabirds as indicators of the marine environment. ICES J Mar Sci. 65(8):1520–1525. doi:10.1093/icesjms/fsn155

Pascoe S, Innes J, Holland D, Fina M, Thébaud O, Townsend R, Sanchirico J, Arnason R, Wilcox C, Hutton T. 2010. Use of incentive-based management systems to limit bycatch and discarding. IRERE 4(2):123–161. doi:10.1561/101.00000032

Pierre JP, Abraham ER, Cleal J, Middleton DAJ. 2012. Reducing effects of trawl fishing on seabirds by limiting foraging opportunities provided by fishery waste. Emu 112(3):244–254. doi:10.1071/MU12002

Pott C, Wiedenfeld DA. 2017. Information gaps limit our understanding of seabird bycatch in global fisheries. Biol Conserv. 210:192–204. doi:10.1016/j.biocon.2017.04.002

Regular P, Montevecchi W, Hedd A, Robertson G, Wilhelm S. 2013. Canadian fishery closures provide a large-scale test of the impact of gillnet bycatch on seabird populations. Biol Lett. 9(4):20130088. doi:10.1098/rsbl.2013.0088

Rojas-Bracho L, Taylor BL. 2017. Vaquita Phocoena sinus The IUCN Red List of Threatened Species 2017: e. T17028A50370296. doi:https://dx.doi.org/10.2305/IUCN.UK.2017-2.RLTS.T17028A50370296.en

Rouxel Y, Montevecchi W. 2018. Gear sustainability assessment of the Newfoundland inshore northern cod fishery. Ocean Coast Manag. 163:285–295. doi:10.1016/j.ocecoaman.2018.05.018

Senko J, White ER, Heppell SS, Gerber LR. 2014. Comparing bycatch mitigation strategies for vulnerable marine megafauna. Anim Conserv. 17(1):5–18. doi:10.1111/acv.12051

Sherley RB, Barham BJ, Barham PJ, Campbell KJ, Crawford RJM, Grigg J, Horswill C, McInnes A, Morris TL, Pichegru L, et al. 2018. Bayesian inference reveals positive but subtle effects of experimental fishery closures on marine predator demographics. Proc R Soc B. 285(1871):20172443. doi:10.1098/rspb.2017.2443

Shivlani M, Letson D, Sawczyn CR. 1998. Socioeconomic effects of the Florida net ban in Monroe County. Fla Geogr. 29:12–29.

Smith S, Jacob S, Jepson M, Israel G. 2003. After the Florida net ban: the impacts on commercial fishing families. Soc Nat Resour. 16(1):39–59. doi:10.1080/08941920309174

Sonntag N, Schwemmer H, Fock HO, Bellebaum J, Garthe S. 2012. Seabirds, set-nets, and conservation management: assessment of conflict potential and vulnerability of birds to bycatch in gillnets. ICES J Mar Sci. 69:78–589.

Tull CE, Germain P, May AW. 1972. Mortality of thick-billed murres in the West Greenland salmon fishery. Nature 237(5349):42–44. doi:10.1038/237042a0

Turner SM, Manderson JP, Richardson DE, Hoey JJ, Hare JA. 2016. Using habitat association models to predict Alewife and Blueback Herring marine distributions and overlap with Atlantic Herring and Atlantic Mackerel: can incidental catches be reduced? ICES J Mar Sci. 73(7):1912–1924. doi:10.1093/icesjms/fsv166

van Beest FM, Kindt-Larsen L, Bastardie F, Bartolino V, Nabe-Nielsen J. 2017. Predicting the population-level impact of mitigating harbour porpoise bycatch with pingers and time-area fishing closures. Ecosphere 8(4):e01785. doi:10.1002/ecs2.1785

Vetemaa M, Ložys L. 2009. Use of by-catch safe fishing gear in pilot project areas. LIFE Nature project "Marine Protected Areas in the Eastern Baltic Sea" LIFE 05 NAT/LV/000100, Action D1 Final Report http://lifempa.balticseaportal.net/media/upload/File/Deliverables/Action%20reports/D1_final_report.pdf.

Villasante S, P, Guimeráns C, Rodrigues J, Antelo M, Rodrígues R, Da Rocha JM, Coll M, Pita C, Pierce G, Hastie L, et al. 2015. Small-scale fisheries and the zero discard target. European Parliament Directorate-General for Internal Policies, Policy Department B Structural and Cohesion Policies, Fisheries. IP/B/PECH/IC/2014-084. https://www.europarl.europa.eu/RegData/etudes/STUD/2015/540360/IPOL_STU(2015)540360_EN.pdf.

Walters C. 2000. Impacts of dispersal, ecological interactions, and fishing dynamics on efficacy of Marine Protected Areas: how large should protected areas be? Bull Mar Sci 66:745–757.

Washington Department of Fish and Wildlife (WA DWF). 2020. Puget Sound Commercial Salmon Regulations. (https://wdfw.wa.gov/sites/default/files/2020-07/2020_comm_final_upload_07192020.pdf).

Wiedenfeld DA. 2016. Seabird bycatch solutions for fishery sustainability. Am Bird Conservancy p. 71. https://abcbirds.org/wp-content/uploads/2015/05/Seabird-Bycatch-Solutions_2016_InternetRequired_LowRes.pdf.

Wild PW. 1990. The central California experience: a case history of California halibut set net laws and regulations In: Haugen CW, editor. The California Halibut, Paralichthys californicus, Resource and Fisheries. San Diego (CA): California Department of Fish. Game Fish Bulletin 174. p. 321–340.

Willison JHM, Côte RP. 2009. Counting biodiversity waste in industrial eco-efficiency: fisheries case study. J Clean Prod. 17(3):348–353. doi:10.1016/j.jclepro.2008.08.003

Zhou S, Daley RM, Fuller M, Bulman CM, Hobday AJ. 2019. A data-limited method for assessing cumulative fishing risk on bycatch. ICES J Mar Sci. 76(4):837–847. doi:10.1093/icesjms/fsy206

Žydelis R, Bellebaum J, Österblom H, Vetemaa M, Schirmeister B, Stipniece A, Dagys M, van Eerden M, Garth S. 2009. Bycatch in gillnet fisheries – An overlooked threat to waterbird populations. Biol Conserv. 142(7):1269–1281. doi:10.1016/j.biocon.2009.02.025

Žydelis R, Small C, French G. 2013. The incidental catch of seabirds in gillnet fisheries: A global review. Biol. Conserv. 162:76–88. doi:10.1016/j.biocon.2013.04.002