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Introduction

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An overview of the impacts of fishing on seabirds, including identifying future research directions

S. C. Votier [1,*], R. B. Sherley [2], K. L. Scales [3], K. Camphuysen [4], R. A. Phillips [5]

[1]Lyell Centre, Institute for Life and Earth Sciences, Heriot-Watt University, Edinburgh EH14 EHS, UK
[2]Environment and Sustainability Institute and Centre for Ecology and Conservation, University of Exeter, Penryn Campus, Penryn, Cornwall TR10 9FE, UK
[3]Ocean Futures Research Cluster, School of Science, Technology & Engineering, University of the Sunshine Coast, Maroochydore, QLD 4556, Australia
[4]Department of Coastal Systems, NIOZ Royal Institute for Sea Research, PO Box 59, 1790 AB, Texel, The Netherlands
[5]British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK
[*] *Corresponding author: e-mail:* s.votier@hw.ac.uk.

Abstract

Knowledge of fisheries impacts, past and present, is essential for understanding the ecology and conservation of seabirds, but in a rapidly changing world, knowledge and research directions require updating. In this Introduction and in the articles in this Themed Set "Impacts of fishing on seabirds", we update our understanding of how fishing impacts seabird communities and identify areas for future research. Despite awareness of the problems and mitigation efforts for >20 years, fisheries still negatively impact seabirds via the effects of bycatch, competition, and discards. Bycatch continues to kill hundreds of thousands of seabirds annually, with negative population-level consequences. Fisheries for forage fish (e.g. anchovy, sandeel, and krill) negatively impact seabirds by competing for the same stocks. Historically, discards supplemented seabird diets, benefitting some species but also increasing bycatch rates and altering seabird community composition. However, declining discard production has led to potentially deleterious diet switches, but reduced bycatch rates. To improve research into these problems, we make the following recommendations: (1) improve data collection on seabird–vessel interaction and bycatch rates, on fishing effort and vessel movements (especially small-scale fleets), and on mitigation compliance, (2) counter the current bias towards temperate and high-latitude ecosystems, larger-bodied species and particular life stages or times of year (e.g. adults during breeding), and (3) advance our currently poor understanding of combined effects of fisheries and other threats (e.g. climate change, offshore renewables). In addition, research is required on under-studied aspects of fishing impacts: consequences for depleted sub-surface predators, impacts of illegal, unreported and unregulated fishing, artisanal and emerging fisheries, such as those targeting mesopelagic fish, have received insufficient research attention. Some of these shortfalls can be overcome with new tools (e.g. electronic monitoring, remote sensing, artificial intelligence, and big data) but quantifying and addressing fishing impacts on seabirds requires greater research investment at appropriate spatio-temporal scales, and more inclusive dialogue from grassroots to national and international levels to improve governance as fishing industries continue to evolve.

Keywords: bio-logging; bycatch; discards; fisheries; forage fish; marine policy; resource competition

Background and motivation for a themed article set

As air-breathers that breed on land, seabirds and humans face similar challenges when fishing. It is unsurprising therefore, they have interacted ever since humans first developed a taste for seafood. Today, however, humans have turned fishing into a global industry that extracts huge quantities of biomass from the seas, which, while providing opportunities for some seabirds (i.e. via waste disposal), more often these activities represent a serious threat to seabird community sustainability with population declines of some species attributable directly or indirectly to fisheries effects (Croxall *et al.*, 2012; Phillips *et al.*, 2016; Dias *et al.*, 2019). Nevertheless, quantifying the direct effect of fishing on seabirds is challenging. This is partly due to the logistical challenge of studying processes that are often far from land and thus difficult to observe, but also because seabird population processes are complicated. They have bet-hedging life-history strategies meaning population-level changes can be slow to manifest and large numbers of cryptic pre-breeders, which only rarely come ashore but have the capacity to buffer losses (Votier *et al.*, 2008a). It can also be challenging controlling for the effect of different stressors on seabirds, which can mask or confound fishing impacts and may change quickly. Moreover, the fishing industry is highly dynamic changing what it catches, where and how, with the potential for complex ecological impacts. Fishing impacts on seabirds is something under considerable flux and therefore requires updating if we hope to restore degraded seabird communities and the ecosystem services they provide, and to ensure fisheries are manged sustainably with consideration of their wider ecosystem ramifications.

Paradoxically, the Anthropocene has generated unprecedented pressure on marine ecosystems while also providing to tools to make it an exciting time to study seabird fishery interactions in detail via the development of miniaturized bio-logging devices and application of "big data" to characterize aspects of the marine environment. To update an overview of this research area, we solicited manuscripts about impacts of

Table 1. Research priorities for understanding impacts of bycatch, competition, and discarding on seabirds.

1. Bycatch	2. Competition between forage fisheries and seabirds	3. Discard provision
1.1. How can we improve long-term global monitoring of mortality? *1.2. What is the extent of cryptic mortality—i.e. loss of dead birds between setting and hauling?* *1.3. What is the survival rate of birds released following gear entanglement?* *1.4. How can electronic monitoring be better applied to estimated mortality rates?* *1.5. How can we ensure monitoring of population-level impacts is maintained and extended to a wider taxonomic and geographic range across all susceptible gear types?* *1.6. What is the synergistic effect of fishery impacts and other stressors such as climate change, disease, and offshore renewables?* *1.7. Which seabird populations are declining because of bycatch mortality or recovering because of reduced bycatch mortality?* *1.8. How can we improve triggers for action and enforcement to assist sustainable management of fisheries?*	*2.1. How can we disentangle the effects of natural variation and fishery impacts on forage fish impacts?* *2.2. How does forage fish behaviour (depth, school size) impact availability to seabirds?* *2.3. What are the behavioural metrics which provide the clearest link to prey abundance and availability?* *2.4. How do we better link seabird energetics with forage fish availability?* *2.5. How can we ensure monitoring of population-level impacts is maintained and extended to a wider taxonomic and geographic range?* *2.6. What is the synergistic effect of forage fishery impacts and other stressors such as climate change, disease, and offshore renewables?*	*3.1. What role have discards played in shaping current seabird community structure worldwide and how will this change in future?* *3.2. To what extent are discards junk-food?* *3.3. How can we ensure monitoring of population-level impacts is maintained and extended to a wider taxonomic and geographic range?* *3.4. What is the synergistic effect of discard availability and other stressors such as climate change, disease, and offshore renewables?*

More information and background is found in the main body of the text—this summary is to highlight outstanding research questions.

fishing on seabirds to be included as a themed set in the *ICES Journal of Marine Science*.

Themed set submissions

Following a call for papers and several deadline extensions, we unexpectedly received only ten submissions, five of these were accepted (Kuepfer *et al.*, 2022a; De la Cruz *et al.*, 2022, García-Barón *et al.*, 2022; Gimeno *et al.*, 2022; Timini *et al.*, 2023). It is unclear why there was so few submissions. In the past 10 years, there were 58 publications on the search topics seabird∗ fishery∗ impact∗ according to Google Scholar (accessed 20 July 2023). We cannot easily explain this low number (nor would we like to speculate why) since we provided several deadline extensions and contacted our network of collaborators to try and garner more interest. Therefore, this introduction, while incorporating the accepted articles, will also reflect on this apparently low level of interest and take the opportunity to provide an overview of our current understanding of this topic and suggest future research priorities.

What has previous research highlighted as the main fishery impacts on seabirds?

Several reviews have already done much to identify fishery impacts on seabirds, which make essential reading (Tasker *et al.*, 2000; Montevecchi, 2001; Furness, 2003; Wagner and Boersma, 2011; Le Bot *et al.*, 2018; Montevecchi, 2023). While some have focused on detailed expositions of specific impacts (e.g. Bicknell *et al.*, 2013; Crawford *et al.*, 2017; Sydeman *et al.*, 2017), they collectively highlighted three main fishery impacts: (1) bycatch (incidental mortality), (2) competition for prey resources, and (3) discard provision. Below, we briefly outline these effects considering recent research, while also highlighting ways to improve research into these problems—with future research directions summarized in Table 1.

Seabird bycatch

First highlighted as a threat to seabird populations in the 1970s (Tull *et al.*, 1972), bycatch in fisheries remains one of the greatest threats to their future (Phillips *et al.*, 2016; Dias *et al.*, 2019). Yet, despite the development of highly effective approaches to reduce fisheries bycatch (Maree *et al.*, 2014; Sullivan *et al.*, 2018; Jiménez *et al.*, 2019), hundreds of thousands of seabirds still die each year; recent estimates suggest 160000–320000 are killed annually by longlines (Anderson *et al.*, 2011), ∼400000 by gillnets (Zydelis *et al.*, 2013), tens of thousands by trawl fisheries (Da Rocha *et al.*, 2021), and thousands by purse-seine fisheries (Carle *et al.*, 2019). Overall, around one-third of all extant seabird species and hundreds of millions of individuals are at risk of bycatch (Dias *et al.*, 2019). It is clear therefore that monitoring seabirds–fisheries interactions and mortality is required on a global scale. This is complicated, however, by the woefully low observer coverage of most fisheries, and programmes, which do not yield data of sufficient quality to determine species identity or provide reliable mortality estimates (Phillips *et al.*, 2013). There is also the major challenge of quantifying cryptic mortality, including loss of seabirds from longlines between setting and hauling (Brothers *et al.*, 2010), and the challenges of recording collisions on trawl warp and net-monitoring cables (Gilman *et al.*, 2013; Kuepfer *et al.*, 2022b). Live captures of seabirds, particularly during hauling, are also common in many demersal and pelagic longline fisheries; these events are not monitored with any rigour in most observer programmes, yet over half of the birds may die subsequently from their injuries (Phillips and Wood, 2020).

To quantify changing mortality therefore requires ongoing monitoring across all gear types and a wide geographic range, but regular onboard human observer programmes can be prohibitively expensive (Kindt-Larsen *et al.*, 2011). Electronic monitoring systems (e.g. automated cameras) on fishing vessels are becoming a useful alternative to improve coverage at greatly reduced costs—for example, they have been mandated within the Exclusive Economic Zones of some nations (e.g. Australian Commonwealth fisheries) but is absent from many fleets, particularly those that operate in Areas Beyond National Jurisdictions (ABNJ, the High Seas). While the data-processing challenges of camera systems are prohibitive at present, machine learning is likely to reduce this problem (e.g. Tuia *et al.*, 2022). Computer-vision algorithms can already detect seabirds in some types of still and video imagery with high accuracy (e.g. Sherley *et al.*, 2010; Xu and Zhu, 2016; Kellenberger *et al.*, 2021), which will minimize data storage and transmission requirements, as well as reducing human observer checks (e.g. Qiao *et al.*, 2021). However, even in these cases, discrimination of bycatch taxon beyond family or genus level is likely to remain a considerable challenge, and video technology may be most effective for monitoring compliance (Glemarec *et al.*, 2020).

Population-level effects

Bycatch can negatively impact seabird demography and has contributed to long-term population declines (Phillips *et al.*, 2016). Although the coincidence of a global rise in fishing effort and seabird population declines hinted at this effect, some of the clearest examples come from long-term demographic studies that tested for correlations between fishing effort and seabird trends or vital rates (Tuck *et al.*, 2001, 2011). Most studies focus on albatrosses and petrels in the Southern Ocean and there is strong evidence for a negative effect of long-line fishing effort on multiple albatross and petrel species (Lewison *et al.*, 2004; Pardo *et al.*, 2017; Gianuca *et al.*, 2019). These effects are especially apparent when controlling for the confounding effects of environmental variation, highlighting the importance of quantifying multiple drivers of demographic change. There are similar examples from other regions; for example, Balearic shearwaters *Puffinus mauretanicus*—Europe's only critically endangered seabird—are predicted to become extinct in 61 years if current bycatch rates continue (Genovart *et al.*, 2016). On a more positive note, population modelling reveals that bycatch mitigation measures—in tandem with terrestrial predator control—have allowed the recovery at the French subantarctic island of a species that is particularly susceptible to bycatch on longlines, the white-chinned petrel *Procellaria aequinoctialis* (Dasnon *et al.*, 2022).

Although widely assumed, negative population-level effects of gillnet bycatch on seabirds are rarely quantified. However, population viability analysis shows that the estimated 35 individuals per year (range: 16–60 birds) killed in gillnets in New Zealand is sufficient to have population-level effects on the endangered, yellow-eyed penguin *Megadyptes antipodes* population, which numbers just 1700 pairs (Crawford *et al.*, 2017). The closure of the Canadian gillnet fishery in 1992—which was responsible for killing thousands of seabirds annually—led to greatly reduced bycatch and concomitant population increases for multiple species of diving seabirds (auks Alcidae, and divers Gavidae) while surface feeders (not impacted by bycatch but reliant on discards) declined (Regular *et al.*, 2013).

Future research on the population-level effects of seabird bycatch should carefully consider the additive and synergistic effects of environmental change and terrestrial management (e.g. predator removal and habitat restoration). Moreover, impacts of fisheries on seabirds remain very poorly known in many regions (the tropics, Asia, Africa), and for recreational, artisanal and, given most mortality is cryptic, also trawl fisheries (but see Zador *et al.*, 2008). A review of which seabird populations are declining because of bycatch mortality or recovering because of reduced bycatch mortality would also be timely.

Mitigation and fisheries governance

Bycatch mitigation tools have been designed and implemented that have greatly reduced mortality rates of seabirds in many fisheries, particularly in Exclusive Economic Zones (Maree *et al.*, 2014; Sullivan *et al.*, 2018; Jiménez *et al.*, 2019; Da Rocha *et al.*, 2021; Timini *et al.*, 2023). However, the lack of monitoring of compliance and seabird bycatch rates, and of robust mechanisms for imposing penalties in the event of a breach of regulations has slowed or hindered uptake, particularly in pelagic longline fisheries in the High Seas, and in national fisheries that lack strong governance (Gilman *et al.*, 2014; Phillips *et al.*, 2016; Jiménez *et al.*, 2020). The situation may improve with the development of new algorithms applied to remote-sensing data, which allow detection of IUU fishing, as well as non-compliance with night-setting requirements that reduce albatross bycatch (Winnard *et al.*, 2018; Park *et al.*, 2023). This needs to be in tandem with development of more effective mechanisms for enforcement.

Fishing area closures can deliver dividends for some seabird populations. For instance, closure of the eastern Canadian gillnet fishery led to increased populations of some vulnerable species (Regular *et al.*, 2013). Around South Georgia (South Atlantic Ocean), implementation of multiple mitigation measures, particularly seasonal closure of the fishery in the austral summer, reduced bycatch from tens of thousands of seabirds to negligible levels (Collins *et al.*, 2021). Elsewhere, however, fishery closures can lead to increased bycatch in adjacent waters where fishing effort may be concentrated, highlighting potential unforeseen effects (Copello *et al.*, 2016).

Fisheries governance also requires tools to trigger action. For instance, the Food and Agriculture Organization (FAO) has introduced voluntary international plans of action (IPOAs) for responsible fisheries, which includes The International Plan of Action for Reducing Incidental Catch of Seabirds in Longline Fisheries (IPOA-s; FAO, 2009). These are to guide stakeholders on whether bycatch levels should trigger action based on a range of thresholds. Best practice recommends implementation of National Plans of Action (NPOAs), yet of the 16 NPOAs globally, few are considered effective for this stated purpose (Good *et al.*, 2020).

Seabird–fishery ecological risk assessments often rely on quantitative analyses of spatio-temporal overlap to identify where, when and which life-history stage or age class are at greatest risk of bycatch (Clay *et al.*, 2019, *Gimeno et al.*, 2023). Such studies have progressed from coarse-scale analyses integrating bird locations from satellite transmitters, and fishing effort from national fisheries or Regional Fisheries Management Organizations (RFMOs) available monthly at 1 or 5° grid cell (Cuthbert *et al.*, 2005; Phillips *et al.*, 2006), to much finer-scale studies that overlap GPS locations of birds with movements of individual vessels tracked using Vessel Monitoring Systems (VMS) or vessel Automatic Identification Systems (AIS) (Clark *et al.*, 2020; Carneiro *et al.*, 2022). Moving beyond mapping of overlaps to improving understanding of the drivers that underlie the spatio-temporal structuring of seabird–fisheries interaction hotspots, and how dynamic these might be over management-relevant timescales, could contribute to better informed risk assessments and management mechanisms (e.g. Hazen *et al*., 2018).

Competition between forage fisheries and seabirds

Seabirds are important marine consumers, eating about ~70–100 million tonnes (Mt) of food annually (Brooke, 2004; Karpouzi *et al*., 2007). While this is similar in magnitude to fisheries annual landings (Zeller *et al*., 2018), most prey taken by seabirds is squid, krill, and small schooling fish (e.g. sandeels, herring, and anchovies; Rountos *et al*., 2015). Fisheries for these forage species only account for ~30% of global catches (Alder *et al*., 2008), but overlap with seabirds in space, time, size classes, and hence, trophic level of the catch (Pichegru *et al*., 2009; Rountos *et al*., 2015; Hinke *et al*., 2017). It is now clear that changes in forage fish abundance affect seabird reproduction and survival (Furness and Tasker, 2000; Cury *et al*., 2011; Robinson *et al*., 2015). Although other forms of competition exist (Sydeman *et al*., 2017; Sherley *et al*., 2017b), most efforts to document seabird–fisheries competition consider that forage fisheries limit access to prey resources with implications for seabird behaviour, demography, and distribution (Bertrand *et al*., 2012; Sydeman *et al*., 2017; Gremillet *et al*., 2018). Nevertheless, seabird–fisheries interactions are complex and difficult to document (Sydeman *et al*., 2017; Sherley *et al*., 2018, 2021), and the size of target stocks vary greatly in response to changing environmental conditions, even without fishing (Checkley *et al*., 2017). As such, the role (if any) that fisheries play in limiting resources for top predators remains unclear (Cook *et al*., 2014; Hilborn *et al*., 2017; Free *et al*., 2021; Koehn *et al*., 2021) or is taxon-specific (Searle *et al*., 2023) highlighting the need to better understand if seabird–fisheries competition occurs and how it should best be managed.

Behavioural impacts of forage fisheries on seabirds

It has long been mooted that the foraging behaviour of breeding seabirds is a sensitive indicator of localized prey availability around colonies (Cairns, 1988; Brisson-Curadeau *et al*., 2017). As such, if forage fisheries are capable of outcompeting seabirds for access to prey through localized prey depletion, then we would expect this to manifest itself as changes in seabird foraging behaviour. Foraging is a highly labile trait, however, and birds may buffer short-temporal or small-spatial scale prey depletion either by increasing effort, adjusting the trade-off between self-maintenance and chick provisioning, or switching to alternative prey (Ballard *et al*., 2010; Smout *et al*., 2013; Campbell *et al*., 2019). Relatively, few studies have demonstrated a correspondence between seabird foraging behaviour and direct measures of prey availability at matching spatial and temporal scales (see Brisson-Curadeau *et al*., 2017). Moreover, characteristics other than abundance may be critical in determining availability or exploitability for seabirds, particularly depth and local density of prey patches (Benoit-Bird *et al*., 2013; Boyd *et al*., 2017; Proud *et al*., 2021).

Perhaps unsurprisingly, the few studies that have directly compared seabird behaviour in the presence and absence of forage fishing have also reported signals in some foraging metrics, but not others. For instance, Peruvian anchovy *Engraulis ringens* depletion by industrial fishing increased foraging distance and sinuosity by Peruvian boobies *Sula variegata*, presumably indicating greater search effort (Bertrand *et al*., 2012). Similar effects have been reported for African penguins *Spheniscus demersus* during fishery closure experiments in South Africa (Pichegru *et al*., 2010, 2012). The birds foraged further from their colonies, spent longer at sea, and covered more distant both underwater (vertical distance) and on the surface (trip length), again suggesting greater search effort (Pichegru *et al*., 2012). However, these effects have not been observed consistently at the three other colonies involved in the experiment (Butterworth and Ross-Gillespie, 2022).

More empirical work is needed to understand which of the usual measures of foraging behaviour (maximum distance, number of dives, trip duration, etc.) offer the clearest link to prey abundance or availability before conclusions can be drawn on the impact of forage fisheries on seabird foraging behaviour (Sydeman *et al*., 2017). A recent review of 13 studies linking seabird foraging behaviour with spatial or temporal changes in prey abundance concluded that foraging distance from the colony, diving depth, and diving activity may be good candidate parameters for detecting changes in food supplies (Brisson-Curadeau *et al*., 2017). The distance that birds travel away from the colony to feed has a straight-forward empirical link to resource competition (Wakefield *et al*., 2013; Jovani *et al*., 2016; Weber *et al*., 2021), and can have a linear relationship with reproductive success (Boersma and Rebstock, 2009). Diving behaviour indicates prey depth, which appears to be an important component in foraging success in both empirical and modelling studies of seabirds (Boyd *et al*., 2015, 2017), even deep-diving species (Proud *et al*., 2021). Ultimately, however, measurements of foraging behavior are difficult to interpret in the context of fisheries competition without information on energetics (Sydeman *et al*., 2017). Analysis of animal-borne camera and accelerometery data can now provide metrics of both prey capture and energy expenditure (Elliot *et al*., 2013; Watanabe and Takahashi, 2013; Manco *et al*., 2022), but these technologies have yet to be used in concert with experimental fishing closures.

Population-level impacts

Fishing competition can impact seabirds sufficiently to negatively influence breeding success and chick condition (Frederiksen *et al*., 2004; Sherley *et al*., 2018, 2021; Searle *et al*., 2023). Cury *et al*. (2011) found that across 14 species in seven ecosystems, below a threshold of one-third of the long-term maximum forage fish biomass, breeding success was reduced and more variable. Thus, "one-third for the birds" may provide a threshold by which stock assessments could be set to reduce detrimental impacts on seabirds.

Collapse of the Humboldt Current anchovy stock due to overexploitation and El Niño led to most striking population-level effect of forage fishing when millions of seabirds died. Despite this, evidence for impacts of forage fisheries on adult seabird survival—the vital rate having the greatest effect on population change—is limited (Frederiksen *et al*., 2004), possibly related to their life-history tactics, dietary flexibility, or because impacts are only manifest when fish levels drop below a low threshold (Robinson *et al*., 2015).

Synergistic/complex forage fishery effects

Understanding the complex ways in which forage fisheries may act synergistically with environmental change is a major research objective. Climate change may alter the strength and direction of forage fishery effects on seabirds. For example, Frederiksen *et al.* (2004) found that an active sandeel fishery and warmer seas had additive negative impacts on black-legged kittiwake *Rissa tridactyla* breeding success and survival, greatly reducing the likelihood that this declining population could recover.

Fishing may also uncouple cues that seabirds use to locate prey, creating ecological traps. Forage fish over-exploitation in South Africa means that juvenile African penguins orientate towards previously productive cold waters with insufficient fish stocks to maintain current population levels (Sherley *et al.*, 2017a).

Discard provision

At least half of all 357 seabird species feed on the millions of tonnes of waste discarded by fisheries each year, with diverse ecological impacts (Votier *et al.*, 2004; Bicknell *et al.*, 2013; Oro *et al.*, 2013) and the potential to support millions of birds (Sherley *et al.*, 2020). This global subsidy is a major factor shaping seabird community structure but remains understudied, which is especially pertinent considering rapid declines in discard production (Heath and Cook, 2015; Zeller *et al.*, 2018).

Positive impacts

For many seabirds, discards are beneficial. They can reduce foraging effort and yield a variety of fitness benefits, leading to population growth (Oro *et al.*, 2013). This is exemplified in European waters where several generalists (e.g. Audouin's gull *Larus audouini*, great skuas *Stercorarius skua*, northern fulmars *Fulmarus glacialis*, and northern gannets *Morus bassanus*) increased rapidly during 1960–1980 when discard production peaked, but have since stabilized or declined (Bicknell *et al.*, 2013; Oro *et al.*, 2013; Church *et al.*, 2019). While evidence for discards as drivers of population change is largely circumstantial, seabirds have benefitted from these food subsidies in the Benguela, western Mediterranean, Canary Current, Northwest Atlantic, Australia, Peru, and across the Patagonian shelf (Real *et al.*, 2018).

Negative impacts

Birds attracted to fishing vessels for discards place themselves at risk of bycatch. This applies for most gear types but is especially problematic for trawl fisheries, which produce more discards than other fishing methods (Gilman *et al.*, 2020). However, batch discarding, or waste retention greatly reduces both the number of birds attending trawlers and cable collisions (Kuepfer *et al.*, 2022b). In other cases, however, some species switch from following trawlers to longliners when discarding stops, leading to higher bycatch rates (Soriano-Redondo *et al.*, 2016). Discards may also represent junk food. Some demersal species (which are normally too deep for seabirds to catch themselves) are lower in fat than forage fish, and although beneficial to adults, may be nutritionally inadequate for growing chicks (Gremillet *et al.*, 2008). Moreover, some discards and offal (e.g. liver) can be high in contaminants such as heavy metals (Arcos *et al.*, 2002). Support for the junk food hypothesis comes from the negative relationship between discard consumption and breeding success in black-browed albatrosses *Thalassarche melanophris* (Kuepfer *et al.*, 2022a), adult body condition in northern gannets (Le Bot *et al.*, 2019), and chick growth/survival in Cape gannets *Morus capensis* (Mullers *et al.*, 2009; Cohen *et al.*, 2014). These results together suggest that discards are not able to fully compensate for natural prey shortages (Kuepfer *et al.*, 2022a). Some discards may also cause seabirds to choke if toxic or armoured (Beneman *et al.*, 2016).

Spatiotemporal variation and discard bans

Discard consumption by seabirds varies in time and space within and among species (Votier *et al.*, 2004, 2008b; Sherley *et al.*, 2018, De la Cruz *et al.*, 2022). For instance, northern gannets frequently scavenge behind vessels in UK waters (Votier *et al.*, 2010, 2013), but not around Iceland, probably because of differences in natural prey and discarded fish availability (Clark *et al.*, 2020). Variability in discard use becomes important considering the global shift in discard production away from the Atlantic and Mediterranean, where there has been extensive research on seabird–fisheries interactions, to regions such as the northwest Pacific (Zeller *et al.*, 2018). We need to do more to understand discard effects away from the small number of well-studied examples.

Discard bans and greater gear selectivity will greatly reduce seabird subsidies in some waters (e.g. European Union, Chile, Norway New Zealand), with inevitable consequences for seabirds (Bicknell *et al.*, 2013; Real *et al.*, 2018). Some seabird assemblages have restructured from mainly forage fish specialists to being dominated by generalists (Church *et al.*, 2019), yet these generalists may prey-switch to offset food shortages with implications for further change in seabird community structure (Votier *et al.*, 2004). Nevertheless, reducing discards is desirable and can be achieved by improving gear selectivity, with potential benefits for birds, marine mammals, and some fish stocks (Heath and Cook, 2014). However, we still have a poor understanding of how changing discard availability affected seabird communities in the past and will continue to shape their future.

Less well-studied fishery impacts on seabirds

As fisheries and the oceans change, new threats have emerged, and we identified several new research areas important for understanding and mitigating fishery impacts on seabirds. We describe these below and summarize the main points in Table 2.

Depleted sub-surface predator populations

Sub-surface predators, including cetaceans, tuna, and billfishes, provide important foraging opportunities for seabirds by driving prey to the surface, but over-exploitation and bycatch has greatly diminished higher trophic-level consumer populations worldwide (Heithaus *et al.*, 2008). The impacts of predator removal by fisheries therefore warrants further research, particularly in the tropics. For instance, in oligotrophic tropical seas, many seabirds are surface foragers and appear to be near-obligate commensal foragers (Miller *et al.*, 2018). Long-term declines in tuna stocks are therefore likely to have had negative impacts, although the recovery of some cetacean

Table 2. Summary of future research directions on impact of fishing on seabirds.

	Current status/problem	Research directions/questions
Depleted sub-surface predator communities	*- Facultative foraging common among seabirds, but sub-surface predator communities are depleted.*	*- Is it possible to determine pre-exploitation baselines to understand long-term change?* *- What are the cost/benefit of these associations?* *- How does seabird behaviour differ between high/low facultative predator abundance?* *- Are tropical species more reliant on facultative foraging than at higher latitudes?*
Illegal, Unreported and Unregulated (IUU) fishing	*- Global issue will huge financial and ecological implications.* *- Challenging to monitor but satellite monitoring is improving and larger-bodied scavenging seabirds have potential as ocean sentinels.*	*- How can we best combine seabird bio-logging and remote sensing to help quantify IUU?* *- What are the impacts of IUU fishing in terms of bycatch, competition, and discard provision?*
Mesopelagic/deep-sea fisheries	*- Emergent fisheries which may transfer large biomass of nutrients to surface.* *- Mesopelagic fisheries may compete with some seabirds.*	*- What is the scale of discard provision/nutrient recycling?* *- Do mesopelagic fisheries compete with seabirds for food?* *- What are the potential indirect effects through changes in ecosystem structure?*
Discarded gear	*- Forms a major portion of plastic waste.*	*- How do we improve monitoring and enforcement of plastic pollution by fishers?* *- What are the relative impacts of fishing and other sources of debris on seabird communities?*
Offshore renewables	*- May exclude fishing to create protected areas.* *- Offshore structures may shift fishing effort.*	*- What are the synergistic effects of fishing change imposed by offshore renewable instillations?*
Deliberate harm	*- Fishers mutilate entangled birds on release from gear, but only reported from some areas.*	*- How do we quantify deliberate harm?* *- What are the social/economic and cultural drivers of deliberate harm?*
Depredation and bait-stripping	*- Cetaceans steal bait or catch but extent and impacts for seabirds little studied.*	*- Use bird-borne and gear-mounted cameras to monitor.* *- Could depredation increase in the face of discard bans or changing food availability?*
Seabirds as bait and food	*- Fishers commonly take birds for food but impact poorly quantified.* *- Subsistence levels for artisanal fleets but may be more significant and commercially important in some instances.*	*- What is the scale, drivers, and consequences of the problem?* *- Are more seabirds being taken for processing and shipped to a commercial market (e.g. in the Canary Current), and if so what and where?*
Light-induced vessel strikes	*- Operational lighting can attract birds, which collide and die.*	*- What is the scale of light attraction to fishing vessels?* *- How can we monitor light attraction in the long term?*
Impacts throughout the annual cycle and on less known life-history stages	*- Impact of fisheries on seabird research biased towards breeding season/immatures but non-breeding may represent > half the annual cycle and immatures > 50% of the population.*	*- Use of bio-logging, remote-sensing, and tissue analysis (e.g. stable isotopes) to reveal more about seabird/fishery interactions throughout the annual cycle and for multiple age classes.* *- Do individual tactics in terms of vessel associations persist throughout the annual cycle?* *- What is the ontogeny of fishery interactions?*
Artisanal and recreational fisheries	*- Lack of monitoring and reporting data prevents accurate estimation of scale of impacts.*	*- Better estimation of scale in data-poor systems.* *- Bio-logging to determine seabird–vessel interactions.*

More detail and citations are provided in the main body of the text.

populations may offer cause for optimism (Lotze and Worm, 2009). Such associations may have changed greatly over time with historical overexploitation of marine mammals in the North Atlantic and Southern Oceans having already uncoupled such relationships (Veit and Harrison, 2017).

Illegal, Unreported and Unregulated fishing

Illegal, Unreported and Unregulated (IUU) fishing is a major but poorly understood threat to marine biodiversity including seabirds (Agnew *et al.*, 2009; Cabral *et al.*, 2018). By acting outside the law, IUU fishing has no incentive to respect measures to improve sustainability such as bycatch mitigation. Quantifying and acting against IUU fishing can yield major gains for fisheries (Cabral *et al.*, 2018).

Seabirds have emerged as sentinels to help us understand the scale and impact of IUU fishing. Vessel-radar detection by loggers deployed on albatrosses have been used in conjunction with GPS and vessel AIS data to quantify fine-scale overlap and potential interactions with undeclared, as well as registered vessels fishing in the Southern Ocean (Weimerskirch *et al.*, 2020; Carneiro *et al.*, 2022). However, radar loggers may not detect short associations, satellite-AIS reception is incomplete, and small vessels are not obliged to use AIS, particularly in domestic fisheries (Arrizabalaga *et al.*, 2019; Carneiro *et al.*, 2022). Hence, the undeclared vessels are not necessarily IUU. In addition, temporary disabling of AIS is not illegal (Welch *et al.*, 2022).

Bird-borne cameras and sound recorders can also reveal information on fine-scale seabird–vessel interactions (Votier *et al.*, 2013; Clark *et al.*, 2022), which could include illegal activities. There is huge potential for the deployment of these technologies on more seabird species in areas of high IUU activity to complement the increased global effort in satellite monitoring of movements of fishing and carrier vessels [combining Synthetic Aperture Radar (SAR), AIS, VMS, and long-range identification and tracking (LRIT)] (Kroodsma *et al.*, 2018; Park *et al.*, 2023).

Impact of new and emerging fisheries

The fishing industry is expanding into new, previously untargeted areas such as the deep sea and mesopelagic. While expansion of the deep-sea fishing industry is unlikely to directly affect seabirds, there may be wider ecosystem consequences such as by altering nutrient transfer from the benthos to the sea surface (Roberts, 2002). Mesopelagic fish are an important food for many seabirds (Watanuki and Thiebot, 2018), and therefore the global expansion of mesopelagic fisheries requires careful management to ensure deleterious ecological impacts are minimized (Hidalgo and Browman, 2019).

Loss or discarding of gear and other fishing debris

In 2018, fishing lost ∼48 kt of plastic gear, which excludes abandoned or discarded gear, making it a major contributor to global marine plastic pollution (Kuczenski *et al.*, 2022). This gear can lead to seabird entanglement at the colony (Votier *et al.*, 2011), or at sea (Phillips *et al.*, 2010), and while there is no evidence that plastic entanglement has population-level impacts, greater monitoring and management is required to reduce and mitigate any deleterious effects. Adult seabirds can also ingest fishing hooks inside discarded offal and non-target catch, and these can be fed to, and then digested by chicks; however, whether this has a long-term toxicological effect is unknown (Phillips *et al.*, 2010). Furthermore, a major portion of the plastics and other marine debris ingested by seabirds originates from fishing vessels, rather than from land (Phillips and Waluda, 2020). Additional research could helpfully address outstanding, questions on the possible impacts of toxic substances included during manufacture, or adsorbed by plastics when floating in the ocean.

Offshore renewables

Offshore renewables (wind, tidal, and wave power) are key to reducing global carbon emissions but may also act in tandem with fishing to affect seabirds. For example, offshore wind farms may act as *de facto* marine protected areas, with potential for localized foraging benefits but also costs via increased collision risk (Inger *et al.*, 2009; Halouani *et al.*, 2020). Nevertheless, such area protection may displace fishing effort, for which the consequences are poorly understood (Campbell *et al.*, 2014) but indicates the need for marine spatial panning that considers the trade-offs between conservation, fishing, and energy generation (Püts *et al.*, 2023). As offshore renewables continue their rapid global growth, understanding more about the potential for interactive effects with fisheries on birds is a clear conservation priority.

Deliberate harm

When removing birds from pole-and-line and handlines, some fishers deliberately kill or injure otherwise healthy seabirds, representing a poorly documented threat (Bugoni *et al.*, 2008; Gianuca *et al.*, 2020). Whether this is limited regionally, e.g. to Brazil hook-and-line fisheries, is unclear. Guidance on how to safely handle and release hooked seabirds is readily available. Reducing the deliberate harm of seabirds requires a system of on-board monitoring, penalties, changing gear configurations, or fishing practices to minimize the period that baited hooks are accessible for surface-feeding seabirds; however, these are challenging to enforce on small vessels, and the key goal is likely to be a change in culture of the fishing community.

Depredation and bait stripping

Marine mammals and sharks are well known to take catches from gear underwater or at the surface (depredation; Collet *et al.*, 2018), but seabirds also exploit such feeding opportunities. For instance, Peruvian boobies *Morus variegata*; take anchovies from purse-seine nets (e.g. Clark *et al.*, 2022), and bait loss to seabirds is pervasive in many longline fisheries (Løkkebor, 1998, Bestley *et al.*, 2020). Therefore, depredation can create conflict between seabirds and fishers (Tixier *et al.*, 2021) and may be the main reason for intentional harming of albatrosses and petrels (Gianuca *et al.*, 2020). Yet, the scale of bait loss in longline fisheries could incentivize the adoption of bycatch mitigation measures (Gandini and Frere, 2012).

Seabirds as food or bait

Historically, fishers have taken seabirds either as bait or for sustenance (Tasker *et al.*, 2000). This still happens, especially within artisanal fisheries, but is poorly documented. There is anecdotal evidence that large numbers of birds are taken for human consumption in the Canary Current and off Peru (Alfaro-Shigueto *et al.*, 2016; Grecian *et al.*, 2016). Further investigation is required on the scale of the problem and impact on seabird populations. As with many other threats, better fisheries governance involving tighter legislation and licence conditions, requirements to improve humanitarian conditions on board vessels, prosecutions in the event of breaches, and educational efforts can be effective in reducing or eliminating intentional take, such as in the Asian squid-jigging fishery in Falkland Islands waters (Reid *et al.*, 2021).

Bird strikes because of vessel lights

Light-induced collisions with fishing and other vessels during darkness are common under certain conditions, particularly fog close to breeding colonies, and can involve tens or hundreds of birds, particularly small species such as burrowing petrels (Black, 2005; Coleman *et al.*, 2022). The risk can be reduced by use of black-out blinds on portholes and windows at night, ensuring decks are free of oil, timely collection, temporary confinement for recovery (to avoid hypothermia), and release of birds, minimizing deck lights, etc. (Black, 2005). However, it is challenging to eliminate entirely if lights are used for safety reasons on deck during fishing, or for forward navigation, particularly in ice. Mitigation via technical solutions include minimizing light pollution, such as light shielding or wavelengths (green lights) that reduce confusion or attraction of birds. Improved monitoring of the numbers and age classes of birds involved, and the contributing factors is also required, as the recording of bird strikes on fishing vessels is much less systematic than that of bycatch on longlines (Collins *et al.*, 2021).

Impacts throughout the annual cycle and on less known life-history stages

Fisheries impacts are studied predominantly during breeding, despite many seabirds associating with fisheries throughout the annual cycle (Clay *et al.*, 2019; Carneiro *et al.*, 2020). Moreover, fisheries can have major impacts, including through overfishing or bycatch, on age classes (immatures) and stages during the annual cycle, such as the non-breeding season, that receive less research attention (Gianuca *et al.*, 2017; Sherley *et al.*, 2017a; Frankish *et al.*, 2021, Gimeno *et al.*, 2022). This is partly influenced by logistics, but remote sensing combined with bio-logging and analysis of tissue composition (e.g. stable isotopes, fatty acids, and DNA metabarcoding) have revealed fisheries interaction year-round (Meier *et al.*, 2017). Studies of movements and survival of immatures are challenging because of the long period (years) spent continuously at sea, and progress is slow even though this was highlighted as a critical knowledge gap more than decade ago (Lewison *et al.*, 2012).

Artisanal and recreational fishing

Despite representing half of global fishing effort (Rousseau *et al.*, 2019), and ~25% of catch (Watson and Tidd, 2018), little is known about the scale or impacts of recreational or artisanal fishing on seabirds, other than these “small-scale” fisheries may represent as great a threat as industrial fisheries to some seabird species or populations (Dias *et al.*, 2019). This is less surprising if consideration is given to the huge number of participants, even if the bycatch rate for an individual vessel is very low (Hughes *et al.*, 2022). Indeed, an estimated 118 million people (10.5% of the population) fish recreationally in North America, Europe, and Oceania (Arlinghaus *et al.*, 2015). Ecological risk assessments provide an effective way to study potential impact of artisanal fisheries (García-Barón *et al.*, 2022) but are more often targeted towards larger industrial fleets (Good *et al.*, 2023). Much more information is required on the effects of artisanal and recreational fishing on seabirds and offering practical solutions to the problem, particularly given the diversity of methods that warrant a toolbox approach.

Concluding remarks

By revisiting some of the research on fishery effects on seabirds, we note important knowledge gaps, that can be summarized as follows: (1) availability of up-to-date, high-resolution data on seabird–vessel interaction and bycatch rates, on fishing effort and vessel movements (especially small-scale fleets), and on compliance with mitigation and other regulations, (2) bias towards temperate and high-latitude ecosystems, larger-bodied species, and particular life stages or times of year, and (3) a lack of understanding of synergistic or additive effects of fisheries and other threats (the global warming, ocean acidification, offshore development for hydrocarbon extraction, or to exploit renewable energy from wind and waves). Yet, we have the tools to overcome many of these challenges. Remote sensing and electronic monitoring used in tandem with a more open and discursive approach to fisheries management lies at the heart of improving compliance and creating more sustainable fishing. Also, we have the skills to address many of these issues (analytical or technical), although the main challenge is financial—biases can in part be attributed to the location of the wealthiest countries or places with the greatest resources. We need to redress this imbalance and build capacity in resource-poor and data-poor settings.

Finally, this overview highlights that fishing is still a major threat to seabird communities—minimizing these impacts is vital to halt or reverse population declines. This imperative should not be lost on the fishing industry, which relies to a considerable degree on the ecosystem services that seabirds provide (Plazas-Jiménez and Cianciaruso, 2020). While fishing may have positives for some seabird communities, these are limited in comparison to negative impacts. Perhaps the plethora of research, including numerous review articles, indicates a perception of “job done” in terms of fishing impacts on seabirds. We do not believe this is the case and hope that by highlighting gaps and research directions (Tables 1 and 2), this may stimulate further research.

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No data relate to this submission.

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