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RESEARCH

Feasibility and knowledge gaps to modeling circumpolar seabird bycatch in the Arctic

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Abstract
Alteration and diminution in sea ice cover in the Arctic region will give rise to an intensification and expansion of fishing activities in the Arctic and associated marginal seas. Increased fishing activity, especially in the summer, could pose a direct threat to the millions of seabirds breeding in this region, as well as non-breeding migrants, and potentially result in an increase of bycatch mortality. To inform what conservation and management actions may be needed, an analysis of where seabirds/fisheries interaction are most likely to occur is required. Here, we establish what information would be required to effectively model circumpolar bycatch risk of seabirds in the Arctic, and then we assess the availability of the requisite data. The quality and availability of fishing effort, and bycatch monitoring effort data are not homogeneous among Arctic countries. Undertaking a true circumpolar analysis at this time would be difficult, and with the current data accessibility, many assumptions would have to be made, potentially leading to caveats in the results. Improved communications between the various agencies and institutes working on fisheries and seabirds would strengthen the quantitative basis for future analyses. We offer suggestions on how to improve bycatch estimates and the identification of high-risk areas for seabird bycatch in the Arctic.

Keywords Bycatch reduction · Gillnet mortality · Longline mortality · Fisheries

Introduction

The incidental take of unwanted animals by commercial fisheries (i.e., bycatch) has been a concern globally for decades (Lewison et al. 2004; Arctic Council 2000). It affects non-targeted fish, but also turtles and marine mammals and is a significant threat for many seabird species (Lewison et al. 2004; Moore et al. 2009; Dias et al. 2019). From the seabird perspective, the loss of adult individuals can especially pose a threat to a population (Lewison and Crowder 2003; Tuck et al. 2011; Phillips et al. 2022), while for the fishing industries, bycatch creates an economic impact, through bait loss and associated lower fish harvest, and time spent removing entangled seabirds from the nets and hooks (Løkkeborg

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2003). A core objective of the ecosystem approach to fisheries management is to reduce and/or eliminate bycatch with the objective that long-term viability of populations of concern is not threatened by bycatch (Pikitch et al. 2004), and research on mitigation measures targeted at reducing seabirds in fishing gear (e.g., Melvin et al. 1999) has been successfully implemented in several fisheries with promising results (Sullivan et al. 2018; Jimémez et al. 2020; Da Rocha et al. 2021). This approach is promoted by the marine stewardship council (MSC) with its seafood ecolabel certification and influenced by consumers asking for more sustainable seafood (Jaffry et al. 2016).

The Arctic, as defined by the Arctic council working group conservation of arctic flora and fauna (CAFF), includes Arctic and sub-Arctic seas, and is home to millions of breeding seabirds (Barrett et al. 2006; Gaston et al. 2012; Irons et al. 2015; Kuletz et al. 2019; Boertmann et al. 2020), and bycatch is a concern, with the potential for an increase on the conflict level as fisheries are either growing or expanding their activities in the region (Haug et al. 2017; Anderson et al. 2018). Multiple seabird species are incidentally caught as bycatch by various types of fisheries (Hedd et al. 2016; Table 1). For instance, surface feeders like northern fulmars (*Fulmarus glacialis*) are caught in demersal longlines (Fangel et al. 2017), while diving birds like black guillemots (*Cepphus grylle*) and common eiders (*Somateria mollissima*) are caught in coastal gillnets in Iceland and Norway (Christensen-Dalsgaard et al. 2019). Considering the economic importance generated by the fishing activities in some regions of the Arctic, knowledge about locations of seabird/fisheries overlap (e.g., Dietrich et al. 2009) is an essential first step to developing and targeting appropriate mitigation measures.

While key bycatch high-risk areas have been identified for some regions (e.g., Davoren 2007), the actual amount of bycatch in the Arctic has been understudied and requires attention (Dawson et al. 2020). Many seabird species breeding across the circumpolar regions, such as thick-billed murres (*Uria lomvia*; Frederiksen et al. 2016), and black-legged kittiwakes (*Rissa tridactyla*; Frederiksen et al. 2012) carry out annual east–west migratory movements. As such, spatio-temporal overlap between fisheries and seabirds, and potential bycatch high-risk areas in the Arctic should be addressed from a circumpolar rather than a single jurisdiction perspective, which often only covers a portion of the annual breeding cycle. In the North Pacific, these same or related species show north–south (Orben et al. 2015; Piatt et al. 2021; Takahashi et al. 2021) as well as east–west migrations post-breeding (e.g., Orben et al. 2018; Drummond et al. 2021; Ezhov et al. 2021; Takahashi et al. 2021), and similarly could be exposed to fisheries in different regions and districts. The Pacific Arctic also has two species of *Ardenna* shearwaters from the southern hemisphere that migrate to the region during summer and early fall (Shaffer et al. 2006; Yamamoto et al. 2015), and three albatross species that nest in the central Pacific that feed in Alaska during the northern summer (Kuletz et al. 2014 and references therein). All of these surface feeding Procellariids are subject to bycatch in longline fisheries (Stehn et al. 2001).

There are several approaches that can be taken to analyze the risk of seabirds encountering fisheries and potentially inducing bycatch. One method consists of tracking seabirds of interest and overlapping their tracks with fishing locations from logbooks, vessel monitoring system (VMS) or vessel trip reports (VTRs) which provide information about the distribution of fishing activity. This indirect method provides a spatial overlap index between seabirds and fishing activities (e.g., Dietrich et al. 2009; Yorio et al. 2010; Roe et al. 2014). The frequency of bycatch events cannot be assessed from such data, but the overlap can be used to estimate the risk of interactions and the risk of bycatch. Other indirect methods include the productivity susceptibility analysis (PSA) used by the MSC; it is a semi-quantitative method based on the demographic information of a species to assess its productivity and on gear type to determine its susceptibility to fishing activities (Good et al. 2024). Finally, tools created for geographic information systems such as bycatch risk assessment (ByRA) relies on existing distribution and abundance data of the species of concern, and fisheries occurrence and interaction rates (Hines et al. 2020). A more direct method relies on the data collected on fishing boats by observers recording bycatch events. However, this method requires considerable human effort to gain enough datapoints for statistically sound analyses, as bycatch is often highly episodic and rare (Wakefield et al. 2018). To address this issue, self-sampling reporting, as in the Norwegian Reference Fleet (Clegg and Williams 2020) and electronic monitoring using closed-circuit television cameras linked to GPS and hard drives for data storage can be used (Glemarec et al. 2020).

Given the ongoing global commitments to manage fisheries using ecosystem-wide, sustainable practices (Cochrane 2021; Huse et al. 2021), there is a need to shift how fisheries managers consider data from other taxonomic groups, such as seabirds. In most jurisdictions, fisheries and bird conservation are tasked to different departments or agencies, often pursuant to different legislation. For example, in Canada, migratory birds are managed by Environment and Climate Change Canada (ECCC), whereas fisheries are managed by Fisheries and Oceans Canada (DFO). However, it is only when the data from both agencies are brought together that a better, and we would argue more meaningful analysis of overlap and interactions is possible. As a step toward producing circumpolar analyses of Arctic seabirds and fisheries overlap, we review here the required information to model circumpolar seabird bycatch, the ease with which these data can be obtained from different agencies across jurisdictions

Table 1 Examples of known bycaught seabird species in the Arctic, with fished target species, fishing period, and gear used

Country	Target fish	Fishing period	Gear type	Main bycatch species	Sources
Russia	Pacific cod, Pacific halibut, black halibut	Year round, mainly May–September	Demersal longline	Northern fulmar Short-tailed shearwater Gull spp.	Artukhin et al. 2006
Russia	Walleye pollock	May–December, mainly June–September	Trawler	Laysan albatross Northern fulmar Short-tailed shearwater Black-legged kittiwake	Artukhin et al 2023
USA	Pacific cod	January–May September–December	Longline, trawler	Northern fulmar Gull spp. Laysan albatross Black-footed albatross	Wohl et al. 1998 Stehn et al. 2001 Melvin et al. 2019
USA	Groundfish and halibut		Trawler, longline	Northern fulmar Shearwater spp.	Krieger and Eich 2021
USA	Salmon (5 spp)	June–September	Set Gillnet Drift Gillnet Seining	Alcidae (primarily murres, murrelets, puffins) Diving ducks, Grebes, Loons, Cormorants	Dietrich and Kuletz 2024
Canada	Greenland halibut	May–December	Trawler Gillnet Longline	Northern fulmar Glaucous gull	Anderson et al. 2018 Johnson et al. 2021 Hedd et al. 2016
Canada	Northern shrimp and striped shrimp	April–December	Trawl	No data available	DFO 2018
Canada	Lumpsucker	June–July	Gillnet	No data available	Christensen-Dalsgaard et al. 2019
Denmark (Greenland and Faroes Islands)	Lumpsucker Cod Haddock	January–May Year round	Gillnet Demersal longline	Common eider Common murre Great cormorant Northern fulmar Eider spp.	Anderson et al. 2011 Merkel 2004, 2011 Christensen-Dalsgaard et al. 2019 Merkel et al. 2022
Iceland	Lumpsucker	March–August	Gillnet	Common eider Black guillemot Common murre Cormorant spp	Christensen-Dalsgaard et al. 2019 MFRI 2019
Iceland	Cod Haddock	January–April Year round	Gillnet Longline Trawl	Northern fulmar Common murre Northern gannet Black guillemot Common eider Great cormorant European shag	Peterson 2002 Žydelis et al. 2013 ICES 2020
Norway	Lumpsucker	April–July	Gillnet	Black guillemot Cormorant/Shag	Christensen-Dalsgaard et al. 2019
Norway	Cod Haddock Saithe	Year round	Coastal gillnet	Common guillemot Northern fulmar Northern gannet Razorbill	Bærum et al. 2019
Norway	Greenland halibut	May–July	Longline	Northern fulmar	Fangel et al. 2017
Norway	Herring	November–February	Purse seine	Herring gull	Christensen-Dalsgaard et al. 2022

in the Arctic region, and what needs to be done for greater accessibility of the data and models with more predictive power. We first reviewed what types of data are needed for a modeling exercise looking at bycatch high-risk areas in the Arctic. We then reviewed the existing access to the available data in different Arctic regions by asking seabird specialists from the Arctic Council Working Group, the CAFF about those data in their respective countries (Canada, Russia, Kingdom of Denmark [including the Faroe Islands and Greenland], Finland, Sweden, Norway [including Svalbard], Iceland, USA [Alaska]; questionnaire available in Online Resource 1). Through this process, we aimed to gain insights into what is lacking in the type of fishery-bird high-risk areas analyses that are needed.

Methods

Study area

The limit of the Arctic in this study was defined by CAFF (CAFF 2021). It encompasses the entire Arctic region, which includes certain sub-Arctic regions, the Arctic Ocean, and its surrounding seas.

Data required for risk assessments

Spatiotemporal data–seabird tracking studies and overlap with fisheries

Information on seabird distribution can be obtained from various types of tracking devices. These devices can be of different size and functionality depending on the intended use (see Bernard et al. 2021). The frequency of fixes (i.e., bird locations) can be user-specified in some devices, such as Platform Terminal Transmitter (PTT) satellite tags and Global Positioning System (GPS)-loggers, and vary from once a minute (or less) for fine-scale study using GPS/Global system for mobile communication (GSM) transmitters to two locations per day for geolocator (GLS) loggers. The precision will also vary according to the type of device (meters for some GPS-loggers to hundreds of kilometers for GLS-loggers; Bridge et al. 2011).

Seabird tracks obtained with tracking devices (PTT or GPS) can be overlain directly with fishing effort (Hyrenbach and Dotson 2003; Weimerskirch et al. 2000; Pichegru et al. 2009). Fishing effort is usually defined as the amount of time (normally reported as days at sea or days fished) spent searching for fish (in an active or passive form) combined with the amount of fishing gear used (e.g., number of hooks or length of fishing net, or area seined). This measure of effort will depend on the fishery and the type of gear used. For example, fishing effort for trawlers may include the number of tows, the tow duration, the distance traveled per day, and the number of days fished, while fishing effort for gillnet operations includes the number of nets set, the number of sets, the length of net set, duration of sets in the water, and the number of days fished. For passive gear fishing, when locations of fishing effort and fishing vessels do not match, it is possible to determine fishing effort locations through logbooks, VMS or automatic identification systems (AIS) data (Lee et al. 2010; Sales Henriques et al. 2023). If fishing data are presented with actual vessel tracks rather than fishing effort, and given high accuracy seabird tracking data, it is possible to calculate the distance between seabirds and fishing vessels using geographic information system (GIS) software (Freeman et al. 2001; Waugh et al. 2005). It is also possible to determine the change in seabird behavior when in close proximity with fishing vessels (Collet et al. 2015; Cianchetti-Benedetti et al. 2018). One limitation of this type of seabird distribution data is that it is acquired from a limited number of individuals from a few select colonies (Online Resource 2). To obtain accurate positions of the fishing vessels, VMS records, AIS, or any GPS tracking systems can be used, as well as paper or electronic logbook data (Nel et al. 2000; Granadeiro et al. 2011; Guy et al. 2013). For example, VMS and AIS data are available through the Global Fishing Watch (www.globalfishingwatch.org) or by request from some of the nations.

When the accuracy of the tracking devices is lower (e.g., data obtained from GLS-loggers), a solution can be to create kernel density contours or distribution models which indicate where the birds are spending most of their time (Phillips et al. 2006; Hedd et al. 2011; Fauchald et al. 2021). This technique can also be used with devices with a higher accuracy (Xavier et al. 2004; Pichegru et al. 2009). Kernel densities can also be applied to the locations of fishing vessels (Nel et al. 2000). The resulting overlap of kernel densities from seabird movements and fishing vessel locations provide a map of high-risk areas of potential interaction (Copello and Quintana 2009). However, gillnet bycatch may not occur near vessels, rather they can be site-specific to set net operations.

When estimating bycatch risk, it is imperative to consider the temporal overlap between seabirds and fishing activity in addition to the spatial overlap (Gandini and Frere 2006; Laich and Favero 2007; Jiménez et al. 2009). Therefore, it is important to understand the annual migratory cycle of a species, to know when it will be in a region and thus overlap with fisheries in this area. In the Arctic, for example, many GPS tracking studies provide information on key areas around colonies (e.g., Paredes et al. 2012; Davies et al. 2021; Patterson et al. 2022). Using flight characteristics (speed, turning angle, and step length), the behavior of GPS-tracked individuals can be determined (i.e., flying, resting, and foraging), and this can produce estimates of fine-scale behavior. These types of data are important to help determine if spatial overlap with fishing activity may lead to elevated risk of interaction or not (Copello and Quintana 2009; Torres et al. 2013).

At-sea survey for seabirds

At-sea surveys are present in all Arctic countries (Table 2). These may be part of oceanographic ecosystem studies or long-term monitoring and research programs

Table 2 Summary of the data available per country. Orange: data present but available with difficulty (i.e., not public, nor shared under any existing data sharing agreements). Green: data available and easily available. We could not acquire information on these parameters for the Faroe Islands

	Russia	USA	Canada	Denmark (Greenland)	Denmark (Faroe Islands)	Iceland	Norway
Tracking							
Fishing vessels' location							
Fishing effort							Data from Norwegian Reference Fleet
Presence of onboard observers	< 5%		0–100% depending on gear, locations	8–65% for offshore fisheries 0% for inshore		1–5%	Data collected by crew members
Observers' data							Data from Norwegian Reference Fleet
Bycatch per unit effort				Depending on species			
At-sea survey							

(e.g., Kuletz et al. 2019; Cushing et al. 2023), including agency fisheries monitoring surveys. At-sea surveys follow a rigorous protocol using trained observers (Gould and Forsell 1989; Tasker et al. 1984; Gjerdrum et al. 2012), with some data archives extending back nearly 50 years (e.g., North Pacific Pelagic Seabird Database; Drew et al. 2015). As technologies have evolved, so have details of the protocol, but all essentially use visual counts of birds along a ship's route (divided into 'transects'), and a set distance from the vessel, with a GPS stamp that allows calculation of seabird density (birds/km^2) for a given area; these are often then aggregated at a selected grid cell size to derive density maps, which can be overlaid with AIS or other ship or fishery data (e.g., Renner et al. 2013; Renner and Kuletz 2015).

Areas of high fishing effort do not always result in high bycatch rate (see Laich and Favero 2007), but for bycatch to happen, fishing operations and seabirds must be present simultaneously. High overlap between seabird tracks or kernel density and fishing effort does not give a numerical indication of the incidence of bycatch and does not convey the temporal dynamics of both entities (Torres et al. 2013). However, areas with high overlap indicate potential high-risk situations that might require direct bycatch monitoring, through increased observer presence or electronic monitoring to inform about the quantitative aspect of bycatch. The combination of qualitative spatio-temporal data from seabird tracking or at-sea survey data, and fishing activity distribution, along with the quantitative data from independent bycatch monitoring (e.g., onboard observers) provides important information on the distribution of high-risk areas and the likely scale of bycatch for affected species.

Data analysis

The quantitative component – onboard fishing boat observers

When overlap occurs, the probability of interaction is highly sex, age, and species dependent, and can even vary among closely related species (Orben et al. 2021; Rebstock and Boersma 2023). Therefore, knowledge of interaction locations and the number of bycatch events per unit of fishing effort is an important tool for bycatch high-risk areas analysis. The fishing effort should be specific to each gear and interactions are also gear dependent.

Observers onboard fishing vessels can record catch composition, regulatory compliance, and gear configuration. They also record the different interactions possible between seabirds and vessels: number of seabirds present around the vessels, number of seabirds attacking the bait, number of seabird/vessel interactions during retrieval and fisheries discards, and the number of bycaught birds (Abello et al. 2003; Reid et al. 2012; Ramírez et al. 2015; Soriano-Redondo et al. 2016). However, bycatch also happens far from the vessels when passive fishing gears are set (e.g., set longlines or pots, and set gillnets) and thus bycatch is typically underestimated (Brothers et al. 2010).

Bycatch data can be recorded spatially but also qualitatively (i.e., the fishing gear used, the target species), or quantitatively with the fishing effort and the number of individuals of each species caught (Laich and Favero 2007; Hedd et al. 2016; Trebilco et al. 2010). Considering the large number and types of fishing vessels, it is financially and logistically impractical to have observers on 100% of the fishing effort, particularly for smaller vessels. Yet, extrapolation of bycatch events from a representative subset of fishing vessels can be misleading as bycatch events are often episodic and sometimes not randomly distributed (spatially or temporally), but it can be dealt with using model stratification. To minimize analytical bias, it is important to ensure that the distribution of monitoring activity represents the full fishery activity as well as practically possible (Benoit and Allard 2009). Furthermore, on some small fisheries (e.g., lumpsucker fisheries in Norway or salmon fisheries in Alaska), the presence of observers is not always possible. Other means of monitoring, such as electronic monitoring, can also be put in place of observers. Despite its numerous pitfalls, such as low accuracy for high-volume fisheries, failure to record some catch or bycatch, considerable human effort to analyze the video, and potential tempering of the electronic monitoring system to hide information (Glemarec et al. 2020), electronic monitoring is a promising alternative to observers, especially with the development of automated steps with machine-learning tools to identify the seabirds (Kellenberger et al. 2021).

Using the data obtained from onboard observations, several statistical analyses can be undertaken to determine the conditions that increase bycatch events. Statistical modeling approaches (e.g., Generalized Linear Models) can be used, which allow testing of various explanatory variables, including time of capture (night/day), moon phase, season, sea conditions, or other variables concerning the fishing boats and fishing gear, and the amount of discards (Weimerskirch et al. 2000; Delord et al. 2005; Louzao et al. 2011; Soriano-Redondo et al. 2016). Bycatch of endangered, threatened, and protected species are usually rare events, so zero-inflated and hurdle models can be practical methods to deal with such distributions (Bærum et al. 2019; Christensen-Dalsgaard et al. 2019; Bi et al. 2021). Thus, it is important for observer programs and those analyzing the bycatch data to determine the balance between an ideal level of coverage and the effort needed to capture episodic bycatch events.

From at-sea survey observations, density of seabirds is calculated to determine the spatial distribution of the species of interest (Guy et al. 2013). In addition, several statistical analyses can be performed to determine the ocean conditions in which seabirds occur. For example, models using bathymetry, bathymetry features, distance to land or breeding colony, sea-surface temperature, primary productivity, and fishing effort (e.g., haul size, hooks/km^2) are variables that can be used in generalized additive models to predict seabird distribution (Renner et al. 2013) and their overlap with a given fishery (e.g., Dietrich et al. 2009). The effect of fishing vessels on seabird distribution can also be determined using seabird and fishing vessel densities in linear regression (Guy et al. 2013). As an example of a general approach, an index of overlap is measured by multiplying the density of seabirds in a specific region (obtained via at-sea survey and generated in a gridded format) by the total number of hooks, or the number of nets set present and the number of hours vessels are within each region (Tuck et al. 2011).

Collectively, the examples above show that considerable work and approaches have already been developed for assessing seabird bycatch risk, and these can be done with relatively few or many variables, and with different types of data on seabird distributions. Consequently, based on years of data and experience, scientists and resource managers have the analytical tools and approaches to predict seabird bycatch, the current limitations in most cases are data.

Data available for the Arctic

To understand the current limitations of the data concerning seabird bycatch high-risk areas, we contacted researchers from the various countries involved with seabird research in the Arctic via the CAFF Seabird Expert Network. Members of this group either provided the information, or passed the request on to their colleagues that could provide the information for their respective region (Table 1). Through this exercise, we identified the current information available regarding seabird bycatch in fisheries operating in the Arctic.

Seabird tracking data

Tracking data recording seasonal and annual movements of Arctic seabirds are widely available (Online Resource 2), and volumes of existing data can be obtained through a variety of publicly accessible databases (e.g., Bird Life International Seabird Tracking Database https://www.seabirdtracking.org/; Movebank https://www.movebank.org/; SEATRACK https://seapop.no/en/seatrack/). The species tracked through the SEATRACK project include both coastal and pelagic, divers and surface feeders, and include many Arctic-breeding species (Online Resource 2) and Movebank also includes non-breeding migrants to the Arctic region. In addition, there is continuous development of new projects involving acquisition of tracking data, and in general, researchers are willing to share such data for applied conservation research. These new data are uploaded on a regular basis by researchers as part of a global effort of tracking. The locations of seabird colonies, as well as foraging radiuses based on species, are also widely available (Frederiksen et al. 2012; Léandri-Breton et al. 2021). While these data are of less use in direct modeling, they can also inform interaction and risk assessments (Anderson et al. 2018). Collectively, seabird tracking data are available and quite easy to access for modeling risk of seabird bycatch. To ensure the validity of the models, it is crucial to ascertain that the small subset of tracked seabirds accurately represents the broader populations.

Fishing vessel locations and fishing effort

Data on fishing locations and fishing effort can be covered by data protection requirements as they are perceived to have economic or privacy implications (Tomasic 2023), and data are not always freely available, nor easy to access (Table 2). A dataset of AIS fishing vessel location and vessel presence is available through the Global Fishing Watch (www.globalfishingwatch.org) and enables researchers to determine seabird–fishing vessels interactions (Orben et al. 2021). One advantage of using data from Global Fishing Watch is that it incorporates fishing vessels from all countries, not just those of origin in the Arctic region, albeit those data are sometimes aggregated. However, VMS and AIS tracking systems requirements are country dependent. For example, AIS is required for all fishing vessels in Iceland, fishing vessels > 15 m in the European Union, but > 19.8 m in the US waters, and are not required in Canada (Iacarella et al. 2020). However, many fishing vessels in some parts of the Arctic are clearly small vessels, not requiring tracking systems, but with potentially more total bycatch events than bigger fishing vessels (Northridge et al. 2020). High-resolution data pertaining to small fishing vessels are often amalgamated spatially or temporally to protect confidentiality agreements with the regional fishing industry and thus more difficult to obtain than seabird tracking data (Tomasic 2023). In such situations, landings declarations can give approximate fishing effort location.

Presence of onboard observers and corresponding data

Observers are present onboard fishing vessels in the Arctic in all countries surveyed, but the coverage varies among countries (Table 2). Data are usually collected from government agencies and the availability is very different from country to country (Table 3). In Norway, the Institute of Marine Research has established a Reference Fleet comprising 16 high-seas vessels and 22 coastal vessels. Data from this reference fleet are self-reported by crew members. In other countries, onboard observers can be limited to offshore fishing only (Greenland), or certain types of fishing and gear type (e.g., vessels > 20 m in groundfish fisheries in Alaska), while other countries try to observe all fisheries. The percentage of overall fishing effort (measured in e.g., days at sea) with onboard observers depends on target fish, gear type, and country. For example, in the Canadian Arctic, observers are absent from the Arctic char (*Salvelinus alpinus*) fishery, while 100% of the offshore shrimp fishing vessels have observers. Data from observers can be very specific, but can also be limited to the number of birds (without species specification), or the total mass of birds caught. In addition, sampling protocols vary among regions and observers on vessels fishing in the same area may be subject to regulations from outside of the Arctic (e.g., Newfoundland, Quebec, or the Maritimes in southern Canada where the vessels offload). Differences in reporting make comparisons that much more difficult (Wheeland 2016).

Generally, bycatch data, and specifically seabird bycatch data, can be sparse, underreported by fisheries, and can be difficult to access or have limited use because of the lack of details in the information collected (Lewison et al. 2004; ICES 2022). For example, in Greenland, fisheries are responsible for documenting seabird bycatch at the landing sites (Merkel et al. 2022). In Canada, DFO is responsible for the collection of all bycatch data but has no seabird management mandate; that is ECCC responsibility. DFO has but does not analyze seabird bycatch data, while ECCC does not have direct access to the seabird bycatch data but need to analyze it (Tomasic 2023). In Alaska, seabird bycatch in offshore groundfish fisheries is monitored regularly and published in annual reports, whereas gillnet fisheries are monitored by NOAA for marine mammal bycatch at one selected fishing district at a time, but not annually nor consistently at a given district; seabird bycatch data are recorded during these studies, and have recently been compiled and analyzed (Dietrich and Kuletz 2024). Overall, this situation

Table 3 Authorities collecting onboard observer's data

Country	Authority	Ease to get those data
Russia	Regional research institutes	Permission on case by case
USA	NOAA (National Oceanic and Atmospheric Administration)	Permission on case by case
Canada	DFO (Fisheries and Ocean Canada), by the region (which for the Arctic region can include data in Newfoundland region, Quebec region, and the Maritime region)	On request, and can be limited by the 'Rule of Five'
Denmark	Greenland's Fisheries License Control Authority	On request
	Faroe Marine Research Institute—Havstovan	On request
Iceland	Marine and Freshwater Research Institute / Directorate of Fisheries	On request, reported to ICES through annual data call
Norway	Institute of Marine Research	

makes it difficult to carry out seabird bycatch assessments on a regular basis. In contrast, for European countries that part of the International council for the exploration of the sea (ICES), bycatch data are available through annual reports of the ICES Working Group on Bycatch of Protected Species, albeit at a fairly coarse spatio-temporal resolution (ICES 2022).

Bycatch per unit effort

To understand how the fishing effort relates to seabird bycatch, the levels of both effort (the number of hooks or nets in the water, or the number of days at sea), and the number of birds caught are needed. This requires fishing effort and bycatch data to be matched in space and time. The more precise measure of fishing effort (hooks and nets in the water, and for how long) is often not available, so landings of the target species are used as a proxy for effort (McCluskey and Lewison 2008). Acquiring an estimate of fish landed (either as a total mass or as a count) in a spatially explicit dataset is challenging: information related to locations is often aggregated as it is seen as private and confidential. It should be noted that the spatially explicit component (the inclusion of latitude and longitude, or even fishing zone) is critical to matching these data with the equivalent seabird information.

Discussion

Climate change is altering the sea ice conditions in the Arctic, facilitating vessel traffic in the region and increasing fishing activities (Rayfuse 2019; Dawson et al. 2020; Ford et al. 2020). As a result, fishing effort will expand and probably increase (Troell et al. 2017; Tai et al. 2019), and unless mitigation techniques are put in place, bycatch events will most likely increase. Incidental bycatch is a global threat to seabirds (Žydelis et al. 2013; Dias et al. 2019), and should be considered a priority threat for Arctic-breeding seabirds as well as non-breeding migrants; all of these seabirds occupy and use the Arctic regions primarily during summer and fall, when fishing activities would most likely occur. While there is a current moratorium on fisheries in the Central Arctic high seas (https://www.dfo-mpo.gc.ca/international/arctic-arctique-eng.htm), this does not apply to waters within the exclusive economic zone (EEZ) of the Arctic nations, which includes the vast majority of the open water in the Arctic (Brigham 2020).

In this paper, we focused on what is needed to conduct analyses of high-risk bycatch areas within Arctic waters, but it should be recognized that most seabirds that use the Arctic do not stay in the Arctic year-round, and consequently are susceptible to bycatch across many regions. One way in which Arctic Council observer states (France, Germany, India, Italy, Japan, Korea, The Netherlands, People's Republic of China, Poland, Singapore, Spain, Switzerland, and the United Kingdom) can work on Arctic projects within their own borders would be to provide fisheries bycatch information for 'Arctic' seabirds from within the observer country (which typically will involve the migration or wintering parts of the birds' annual cycle).

To determine high-risk areas for seabirds/fisheries interaction across the Arctic, we need access to circumpolar data, but the current data are neither equivalent, standardized, harmonized, nor accessible across the different countries. To improve this situation, we suggest the following steps:

1. *Strong communication between national government agencies (e.g., between DFO and ECCC in Canada) to facilitate annual/regular data sharing and a better harmonization of data collection among regions.* At present, this communication is hindered in some countries. For example, in Canada, if fishing activities in a specific area are the sole responsibilities of a few large vessels, data related to landings and fishing route may be withheld under the "rule of five," whereby under Canada's *Privacy Act*, data are aggregated to a minimum of five data sources (Tomasic 2023). Limited communication between agencies may weaken the effectiveness of seabird conservation (Lescroël et al. 2016).

2. *International collaboration among countries operating fisheries in or regulating fishing in Arctic waters.* The Arctic Migratory Birds Initiative (AMBI), a project under the CAFF working group of the Arctic Council provides a framework to standardize data collection protocols. Data should be made available within a reasonable timeframe after acquisition to ensure use in conservation focused questions.

3. *Freely available seabird tracking data. Many data are collected but their dissemination can be challenging*. Tracking data should include birds of both sexes, but also immature as well as adults, as distribution can be sex and age-specific for some species, and influence the probability of bycatch (Gianuca et al. 2017). Again, tracking data should be made available within a reasonable timeframe after acquisition.

4. *Freely available at-sea survey data, including funding and institutional support for collaboration with vessel-based fisheries monitoring and for data archiving*. While there are regional entities providing this service, it is often limited in spatial scope to a specific region, and support is not consistent. Improved standardization, to the degree practical, of protocol methods, and archival format would improve cross-regional analysis and comparisons.

5. *International collaboration to develop comparable alternative methods to identify origin of bycatch individuals*. On wintering grounds, birds can originate from different breeding populations, but stable isotopes analysis, genomic

approaches, and trace elements profiles could help determine the affected breeding populations (Gómez-Días and González-Solís 2007; Lavers et al. 2013; Colston-Nepali et al. 2020).

6. *Mandatory tracking system (VMS, VTR, or AIS) deployment on fishing vessels of all sizes*. This is already in place in some regions. For example, the current dataset from the Global Fishing Watch does not include gillnet fishing in Davis Strait and Baffin Bay, yet we know such fishing for groundfish using gillnets occurs in those waters (Whidden and McFarlane Tranquilla 2016) and results in seabird bycatch (Hedd et al. 2016).

Although there have been active fisheries in the Arctic for centuries, changing sea ice conditions are opening up new areas, and increasing threats to non-target species. While our present work focused on seabirds, many of the recommendations could be applied to other mobile taxa such as cetaceans, pinnipeds, and elasmobranchs. We already have some tools to minimize most non-target bycatch (Werner et al. 2006), reducing damage to equipment and economic losses for fishers, while improving conservation of seabirds (Hamilton and Baker 2019; Melvin et al. 2019). In this changing world, we need to keep maintaining long-term data and we urgently need to improve collaboration between agencies within countries, and then among countries, to share data and best practices so management measures can be developed to improve seabird conservation and minimize the impact of bycatch on fishing operations.

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Declarations

Competing interests The authors declare no competing interests.

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