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Review

The incidental catch of seabirds in gillnet fisheries: A global review

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ABSTRACT

Based on bird feeding ecology we identified 148 seabird species as susceptible to bycatch in gillnets, of which 81 have been recorded caught. The highest densities of susceptible species occur in temperate and sub-polar regions of both hemispheres, with lower densities in tropical regions. Gillnet fisheries are widespread and particularly prevalent in coastal areas. A review of reported bycatch estimates suggests that at least 400,000 birds die in gillnets each year. The highest bycatch has been reported in the Northwest Pacific, Iceland and the Baltic Sea. Species suffering potentially significant impacts of gillnet mortality include common guillemot (*Uria aalge*), thick-billed guillemot (*Uria lomvia*), red-throated loon (*Gavia stellata*), Humboldt penguin (*Spheniscus humboldti*), Magellanic penguin (*Spheniscus magellanicus*), yellow-eyed penguin (*Megadyptes antipodes*), little penguin (*Eudyptula minor*), greater scaup (*Aythya marila*) and long-tailed duck (*Clangula hyemalis*). Although reports of seabird bycatch in gillnets are relatively numerous, the magnitude of this phenomenon is poorly known for all regions. Further, population modelling to assess effects of gillnet bycatch mortality on seabird populations has rarely been feasible and there is a need for further data to advance development of bycatch mitigation measures.

Contents

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1. Introduction

The status of seabird populations is deteriorating faster compared to other bird groups, and bycatch in fisheries is identified as one of the principle causes of declines (Croxall et al., 2012). The problem of seabird bycatch in gillnet fisheries has long been known in the Pacific, Atlantic oceans and Baltic Sea (Tull et al., 1972; Ainley et al., 1981; Piatt and Nettleship, 1987; Stempniewicz, 1994), and gillnets have been the cause of some of the highest recorded mortalities of seabirds worldwide. In the North Pacific, drifting gillnets were estimated to be killing c. 500,000 birds per year, prior to a UN moratorium in 1992 (DeGange et al., 1993; Uhlmann et al., 2005). A review by Robins (1991) found 60 species of seabirds had been reported caught in gillnets worldwide, and that net mortality was a major contributor to declines of auk populations in California, Newfoundland, the Canadian Arctic, west Greenland and northern Norway. A regional review revealed that between 100,000 and 200,000 seabirds could be being killed annually in gillnets in the Baltic and North Sea region alone (Žydelis et al., 2009).

Surprisingly, the global magnitude and significance of seabird bycatch in gillnet fisheries remain largely unknown (Robins, 1991; Žydelis et al., 2009). Assessment is hampered by large and diverse artisanal fisheries (i.e. small-scale fisheries for subsistence or local markets, typically using traditional fishing gears and small boats), and data on fishing effort and catch of target and non-target species are very sparse.

The objectives of this review were to:

- identify seabird species susceptible to and impacted by gillnet fishing;
- summarise seabird bycatch in gillnet fisheries globally by region and identify likely data gaps;
- assess factors determining bird captures in gillnets;
- review bycatch mitigation measures in use or under development;
- identify areas where conservation actions are most needed.

2. Materials and methods

2.1. Literature search

We reviewed a broad array of scientific publications, published and unpublished reports to collate available data on seabird bycatch in gillnet fisheries worldwide. We identified literature sources by querying the Internet and academic databases (e.g., ISI Web of Knowledge and Zoological Record (TM)), and examining reports otherwise known to authors of this review. Our focus was on existing fisheries, although where useful we mention fisheries that are no longer active.

Due to the high variability in metrics used when assessing and reporting seabird bycatch in gillnet fisheries (Žydelis et al., 2009), it was not possible to summarise the studies in a standardised way. We therefore summarised results by pooling the reported bycatch estimates from non-overlapping regions. We included all information available, including some based on small sample sizes, on the assumption that they represent the best available knowledge to date.

We focused this review on seabird bycatch in marine waters only and considered only seabird species listed in Croxall et al. (2012). We summarised the results by ocean regions using the FAO fishing area boundaries (http://www.fao.org/fishery/area/search/en), some of which were grouped (Fig. 1).

2.2. Gillnet fishing methods

Gillnets are a non-mobile fishing gear with a mesh that traps fish and other organisms. Mesh sizes vary according to target species, ranging from 15 mm to over 250 mm. The net acts as a wall that is weighted or anchored at the bottom and buoyed at the top (the "float" or "cork" line) to keep it vertical in the water column. This blocks the pathway of larger organisms, creating a risk of entanglement for non-target species such as seabirds, turtles, sharks and marine mammals. The gillnet is known as a "fixed gillnet" or "set-net" if it is attached to the seabed by a weighted anchor at each end. The gillnet is a "driftnet" if it is suspended in the water column (one end is buoyed and the other is attached to the stern of a fishing vessel or buoy). Traditionally, nets were made from hemp, cotton or multifilament nylon, which were usually highly visible to seabirds. In recent decades, monofilament has been increasingly used, being cheaper, longer lasting and easier to handle, but also less visible to seabirds and other non-target taxa, increasing the potential for bycatch. In 1992, the United Nations imposed a moratorium on the use of large-scale (>2.5 km long) driftnets on the high seas (U.N. Resolution 46/215), but small-scale driftnetting continues and driftnets, set-nets and other types of gillnets (e.g., trammel nets) persist within many EEZs. Analysis of gillnet fishing effort revealed that this type of fishing takes place in nearshore waters of all continents except Antarctica, and is the most intensive along coasts of SE Asia and in the NW Pacific (Waugh et al., 2011; Sea Around Us Project, 2013). In this review we considered reported bird bycatch in all types of gillnets.

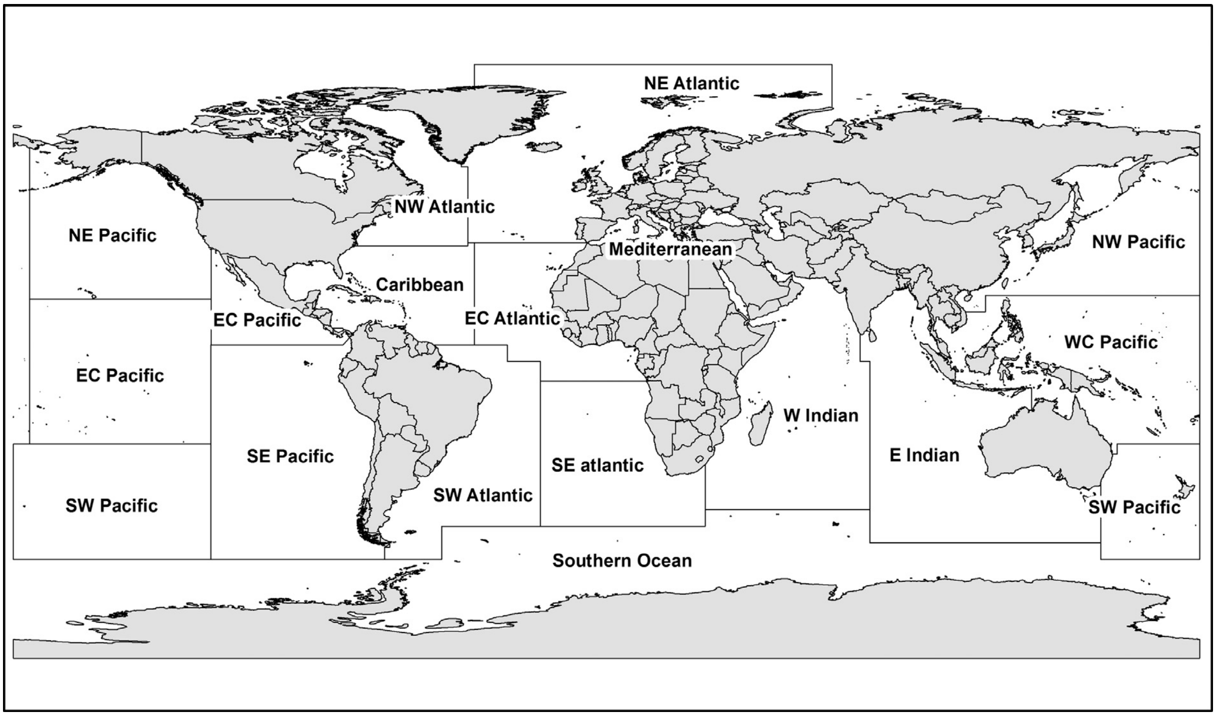

Fig. 1. Ocean regions used for reviewing seabird bycatch in gillnet fisheries. Region boundaries are roughly based on FAO fishing area boundaries.

2.3. Seabird susceptibility to bycatch in gillnet fisheries

The bird species most susceptible to entanglement in gillnets are those that forage by diving for fish or benthic fauna. Susceptibility we define as characteristic that is irrespective of population size and indicates higher probability of being caught in the nets compared to non-susceptible species. The species and number of individuals caught by gillnets are also affected by factors such as mesh size, setting depth, time of day, the length of time that the net is left to soak, water transparency, weather conditions and setting location in relation to seabird abundance.

By reviewing 343 world seabird species (as listed by Croxall et al., 2012) we identified 148 species that are potentially susceptible to entangling in gillnets due to their foraging behaviour, of which 81 have been recorded caught in fishing nets (Appendix). Additionally, 23 surface foraging species were recorded caught in the nets, which we did not identify as susceptible (Appendix, Table 1), however these species never dominated the composition of bycatch. In principle, a gillnet might entangle any bird that comes into contact under different circumstances, and there are records of gillnets trapping dabbling ducks (R. Žydelis personal observations), shorebirds (Manly, 2009) and even a barn owl (*Tyto alba*, Norman, 2000). Marine birds that have been recorded caught in gillnets, but are not listed as susceptible in Appendix, include species which likely entangled during the net hauling or setting (e.g., storm-petrels, gulls; Soczek, 2006) or were trapped when scavenging a net drifting at the surface (e.g., gulls, kittiwakes, storm-petrels; DeGange et al., 1993; Artukhin et al., 2010).

The taxonomic groups with most susceptible species were cormorants, auks, shearwaters, penguins and seaducks (Table 1). Considered together, seabirds susceptible to bycatch in gillnets occur across all oceans, but species diversity is highest in temperate and sub-polar regions (Fig. 2). The list of susceptible species includes 5 Critically Endangered, 14 Endangered, 29 Vulnerable, and 15 Near Threatened species on the IUCN Red List (IUCN, 2012), with the remainder (85 species) being classified as Least Concern (Appendix).

Table 1
Taxonomic groups and numbers of seabird species that were identified as susceptible to fisheries bycatch based on their foraging technique, and actual records of species caught (see Appendix).

Taxonomic group	Total number of species	Number of species identified as susceptible	Number of species reported as bycatch
Steamerducks	4	4	0
Diving ducks	1	1	1
Seaducks	13	13	11
Penguins	18	18	5
Loons	5	5	5
Albatrosses	22	3	8
Giant-petrels	2	0	2
Fulmars	2	2	2
Petrels	54	10	4
Shearwaters	22	22	13
Storm-petrels	23	0	3
Diving petrels	4	4	0
Grebes	4	4	4
Tropicbirds	3	0	0
Frigatebirds	5	0	0
Pelicans	3	0	1
Gannets & boobies	10	10	3
Cormorants	29	29	12
Phalaropes	2	0	0
Gulls, terns, skuas, jaegers, kittiwakes	94	0	11
Auks	23	23	19
TOTAL	343	148	104

3. Results – seabird bycatch by ocean regions

3.1. Northeast Atlantic

This region encompasses the northeast Atlantic bounded by longitude 42 W and latitude 36 N (Fig. 1). The area is home to millions of auks breeding on islands and rocky costs; seaducks are especially numerous in the Baltic Sea; pelagic areas are frequented

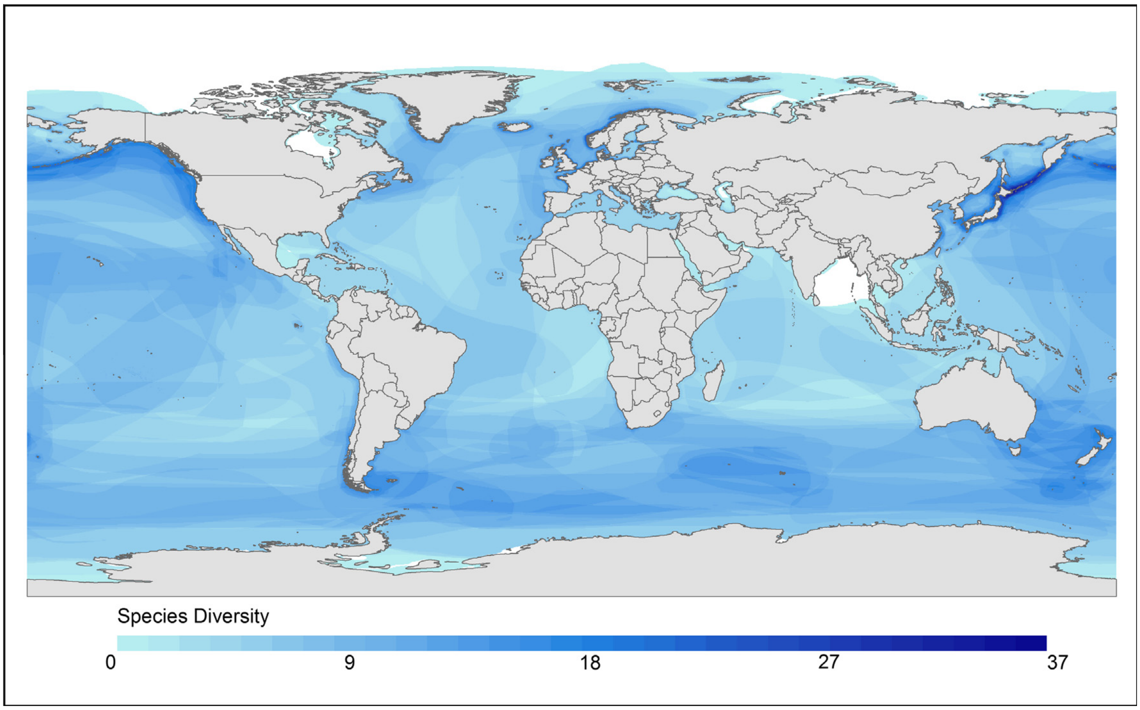

Fig. 2. Global distribution of seabird species susceptible to bycatch in fishing gillnets. The map was created by overlaying species range maps (BirdLife International and NatureServe, 2012). Dark areas represent areas where many susceptible species are located.

by northern fulmars (*Fulmarus glacialis*) and northern gannets (*Morus bassanus*). This region also supports intensive gillnet fisheries, and substantial data exist on interactions with seabird species, compared to other areas.

3.1.1. Baltic Sea

Seabird bycatch in gillnets has been documented in the Baltic since the early 1980s. Žydelis et al. (2009) reviewed 30 studies, mostly based on data from cooperating fishermen, and estimated that at least 76,000 birds were being killed in the Baltic Sea each year. This mortality is thought to have decreased in recent years, driven by the severe decline in seaduck populations (Skov et al., 2011). Bellebaum et al. (2013) estimated an annual bycatch of 17,550 birds along the eastern part of the German Baltic coast, and suggested that annual bycatch had at least halved since the early 1990s, most likely due to population declines. It is also possible that gillnet fishing effort declined during this period, however there are insufficient data to support this (Sonntag et al., 2012; Bellebaum et al., 2013).

Žydelis et al. (2009) found that bycatch species composition in the Baltic Sea generally reflects species distribution, with seaducks predominating in the east, seaducks and diving ducks in the south, and auks in the west. However, taking species abundance into account, pursuit-diving birds, such as loons, grebes, auks and cormorants were found to be more susceptible to bycatch than benthivorous ducks; an earlier study indicated that loons were about ten times more likely to be caught in nets than long-tailed ducks (*Clangula hyemalis*) (Dagys and Žydelis, 2002).

A recent Danish study, unavailable for the review by Žydelis et al. (2009), estimated 841 birds caught in gillnets around the island of Ærø in 2001–2003, mostly common eiders (*Somateria mollissima*), the most common waterbird species in the area (Degel et al., 2010). This study covered only a small part of Danish waters, which is home to hundreds of thousands of wintering waterbirds (Petersen and Nielsen, 2011).

Žydelis et al. (2009) assessed the impacts on three species using a potential biological removal approach, and concluded that gillnet bycatch could be a threat to greater scaup (*Aythya marila*), common guillemot (*Uria aalge)* and long-tailed duck. (Potential biological removal or PBR method allows the assessment of additive mortality on a population with minimum demographic information (Dillingham and Fletcher, 2011 and references therein).) Bellebaum et al. (2013) reached similar conclusion about the long-tailed duck. Further, Steller's eiders (*Polysticta stelleri*), classified as Vulnerable by IUCN (2012), were regularly caught in gillnets on the coast of Lithuania while this species was still wintering there (until 2009, M. Dagys pers. com.), and up to 50 birds of this species die annually in gillnets in Estonia (Žydelis et al., 2006).

While the number of birds being killed per year in some areas is likely to have decreased as a result of population declines, information on bycatch occurring in previously unreported areas suggests that the Žydelis et al. (2009) estimate of 76,000 birds killed per year in the Baltic Sea is probably still a realistic estimate.

3.1.2. Norwegian Sea

In the 1980s, very high bycatch was recorded in salmon and cod gillnet fisheries along the Norwegian coast. Strann et al. (1991) estimated over 100,000 birds killed per year, primarily auks. Since then, there has been a reduction in fishing effort as well as bird populations (Fangel et al., 2011). An interview-based study in 2009–10 estimated 7–8000 birds caught annually in nets set for salmon, cod and lumpsucker (*Cyclopterus lumpus*) in northern Norway (Fangel et al., 2011). It should be noted, however, that episodic incidents of high catches of birds (e.g. 200 common guillemots caught at once) were excluded from these calculations due to their unknown frequency, and further work is planned to improve estimates. In addition, no data were available from several other fisheries. Northern fulmar and black guillemot (*Cepphus grylle*) were most often caught (Fangel et al., 2011).

3.1.3. North Sea and Atlantic Iberia

Data on seabird bycatch in this area are relatively sparse. There are no systematic studies on bird bycatch on the eastern coast of the North Sea. However, occasional bycatch incidents have been reported: 340 common and velvet scoters (*Melanitta nigra* and *M. fusca*) drowned at one location of the Danish sector of the North Sea in one night in March 1987 (Durinck et al., 1993).

On the Atlantic coast of the Iberian Peninsula, Munilla et al. (2007) linked the collapse of common guillemot population to bycatch in gillnet fisheries after the introduction of synthetic netting material. Similarly, Velando and Freire (2002) analysed the decline of European shag (*Phalacrocorax aristotelis*) on the Galician coast of Spain, and concluded that bycatch in gillnets was responsible for reduced adult survival. The same study also found that bycatch had increased as a proportion of the reported causes of mortality of auks from less than 10% before 1970 to nearly 60% in the late 1990s. Based on fishermen interviews, Arcos et al. (unpublished data, 1996) estimated more than 3000 shags and cormorants and over 2000 auks caught in gillnets in Galicia each year.

In Portugal, the gillnet fleet consists of over 8000 registered vessels, 95% of them being less than 10 m long. A questionnaire survey of captains in 2010–2012 found that, of 80 respondents, 64% reported at least one annual bycatch event of seabirds. Northern gannet was identified as the most frequently caught species, followed by auks, gulls, shags, common scoters, shearwaters, storm-petrels and terns (SPEA and University of Minho unpublished data, 2012). The study highlighted the need for further detailed investigations.

In the UK, Murray et al. (1994) estimated that about 2400 auks (1700 guillemots and 700 razorbills *Alca torda*) drowned in salmon nets in NE Scotland in 1992, however most of this fishery has since been bought out and discontinued. There have been no comprehensive UK studies since then, but there are occasional reports of bycatch events, such as the 200 guillemots and razorbills caught near St Ives in one night in January 2012 (RSPB, 2012a) and seabird bycatch recorded in Filey Bay (RSPB, 2012b). Although there may be some local colony impacts, it is generally assumed that bycatch in gillnet fisheries in the UK is not a significant threat to birds at a regional scale and UK colonies of auks have been growing (BirdLife International, 2004).

In SW Ireland, Rogan and Mackey (2007) analysed data collected by observers in offshore driftnet fisheries for albacore tuna (*Thunnus alalunga*). Although these fisheries were highly detrimental to sharks and cetaceans, bycatch of seabirds was relatively modest: 25 seabirds were estimated caught in 1996, and 137 (all Manx shearwaters *Puffinus puffinus*) in 1998. These fisheries are no longer active following the total ban of driftnets for EU fleets by the Council of the European Union (1998), although there have been calls to re-open them.

Although available information from this sub-region suggests that bird bycatch in gillnets may be at a smaller scale compared to other regions, bycatch on the Atlantic coasts of Portugal and Spain is likely to be influencing population declines. Elsewhere, numbers and impacts may be lower, but data remain sparse.

3.1.4. Iceland

Some of the largest seabird colonies in the world are found in Iceland and these include millions of diving birds (BirdLife International, 2004). At the same time, fisheries are an important industry and use a variety of fishing gears including gillnets.

Petersen (2002) reviewed information from ringing recoveries, sales of bycaught birds and studies in the lumpsucker fishery in the 1980s and 1990s. As many as 70,000 guillemots, the majority being common guillemots, were estimated killed in gillnets in 1997, with an overall estimate of 100–200,000 seabirds killed per year in Icelandic gillnet and longline fisheries (Petersen, 2002). Ringing data indicate 20 species of seabirds caught as bycatch, with the lumpsucker fishery reporting the highest number of ringed birds (Petersen, 2002). Black guillemot and red-throated loon (*Gavia stellata*) may be the most susceptible species in proportion to their populations. However, of four studies of common eider and black guillemot bycatch in the lumpsucker fishery, none identified significant impacts on populations (Frederiksen and Petersen, 1999; Petersen, 2002).

In the absence of more recent data, the estimate of 100–200,000 birds killed per year (Petersen, 2002) represents the only available figure, but is considered likely to still stand (A. Petersen, pers. comm.).

3.1.5. Faroe Islands

In the Faroe Islands, the gillnet fishery is small and takes place in deep waters, and is therefore believed to catch few birds. However, no formal investigation has been conducted (ICES, 2010).

3.2. Mediterranean Sea

Compared to other regions, the number of seabird species susceptible to bycatch in gillnets is low, but includes two of the most threatened seabirds in Europe: Balearic shearwater (*Puffinus mauretanicus*) and yelkouan shearwater (*P. yelkouan*). Despite several international and regionals bans on gillnet fishing, fishers from various countries continue to use driftnets within Mediterranean waters (e.g. Tudela et al., 2005). However, data on seabird bycatch in gillnets are scarce.

Louzao and Oro (2004) showed that Mediterranean shag (*Phalacrocorax aristotelis desmarestii*, a subspecies of the European shag) is caught in gillnets in the Balearic Islands, and it is thought that gillnetting could pose a significant threat to this subspecies (De Juana, 1984; Muntaner, 2004). Regular bycatch of shags was also reported for the Iberian coast, as well as bycatch of razorbills, red-breasted mergansers and great cormorants (*Phalacrocorax carbo*) (SEO/BirdLife, unpublished data). There are no recent reports of shearwater bycatch in gillnets in Spain, although this was reported in the past (Besson, 1973). The Hellenic Society for the Study and Protection of the Monk Seal reported that up to 500 yelkouan shearwaters had been caught in a single drift net in Greece (ICES, 2008). In contrast, Tudela et al. (2005) found no evidence of seabird bycatch in the large scale Moroccan driftnet fleet.

Fragmented knowledge from the Mediterranean Sea (cited above) indicates that seabird bycatch in gillnets may be occurring at lower levels than elsewhere globally, but that impacts may be occurring on one or more species and that more data are needed. We did not find any reports on seabird bycatch from the Aegean Sea and the Black Sea.

3.3. Northwest Atlantic

Like the northeast Atlantic, the coastal waters of the northwest Atlantic have a high concentration of species susceptible to gillnet bycatch, including auks, fulmars, seaducks, loons, gannets and cormorants (BirdLife International, 2004). Migrating and staging shearwaters are also seasonally abundant in nearshore and offshore waters.

3.3.1. West Greenland

Greenland is an important area for cliff nesting seabirds with large populations of auk species. Historically, these birds experienced very high human-caused mortality due to intensive hunting and the commercial gillnet fishery for salmon, the latter killing an estimated 500,000 birds per year in the late 1960s to early 1970s (Tull et al., 1972). This mortality was associated with declines of thick-billed guillemots in Greenland (Evans and Waterstone, 1978). Since 1976, salmon gillnetting has been restricted to Greenland fishermen only and bird bycatch estimates fell to 50–100,000 per year by the early 1980s (Evans, 1984) and subsequently fell further. Based on fishermen interviews, Falk and Durinck (1991) estimated that less than 3000 guillemots drowned in salmon gillnets in West Greenland in 1988. The commercial salmon fishery has been reduced greatly since the early 2000s allowing only a limited subsistence harvest (Ad Hoc Review Group, 2008), which likely further reduced seabird bycatch.

However, while bycatch in the salmon fishery has declined, birds are also caught in the lumpsucker fishery. Merkel (2004) studied harvested and bycaught eiders sold in Nuuk, Greenland in 2000–2001 and estimated that at least 2024 eiders were being killed per year in the Nuuk area (90% of birds common eiders, 10% king eiders *Somateria spectabilis*). From 2002 it became mandatory to report bird bycatch as part of the annual hunting statistics. Data from 2003–2008 confirm common eiders and king eiders as the most commonly bycaught birds. Other species were reported in low numbers, including common guillemots, great cormorants, little auks (*Alle alle*), black guillemots, common loons and black-legged kittiwakes (*Rissa tridactyla*, Merkel, 2011). While the average annual reported bycatch in 2003–2008 was 3260 eiders caught mostly in lumpsucker fishery, using an alternative estimate Merkel (2011) suggested that the number could be as high as 6000 to 20,000 eiders killed per year in the lumpsucker fishery alone. Merkel (2011) concluded that the impact of bycatch mortality on species other than eiders is negligible.

3.3.2. Atlantic Canada

During the 1970s and 1980s, there was a major gillnet fishery for Atlantic cod (*Gadus morhua*) off the coasts of Newfoundland and Labrador, responsible for approximately 27,500 birds killed per year, 80% of them being common guillemots (Piatt and Nettleship, 1987). In 1992, fisheries for Atlantic cod were closed. However, gillnets have remained in use in other fisheries and, since 2001, near-shore cod fisheries have been intermittently reopened (Benjamins et al., 2008).

Benjamins et al. (2008) estimated that 5000 to 10,000 common guillemots, >2000 shearwaters (mainly great shearwater *Puffinus gravis*), and several hundred loons, gannets, Atlantic puffins (*Fratercula arctica*) and black guillemots were captured in Newfoundland and Labrador each year, mostly in cod and lumpsucker gillnet fisheries. Benjamins et al. (2008) suggested that current levels of bycatch probably do not impair populations of most affected species; however mortalities of guillemots and shearwaters are of potential concern. Davoren (2007) identified a high spatial and temporal overlap between seabirds, mostly common guillemots, and gillnet fisheries for cod off NE Newfoundland. The author estimated that 3053–14,054 guillemots were killed in this hotspot each year, a number which is high compared to estimates for the area as a whole (Davoren, 2007; Benjamins et al., 2008), suggesting that the regional total could be higher. Analysing historic trends of common guillemots breeding in Newfoundland, Regular et al. (2010) demonstrated that gillnet fisheries were among important factors driving changes in population dynamics between 1980–2006.

In the Maritimes region, annual bycatch of 275 birds (range 0–700) was estimated in the winter flounder and pollock fisheries from 2002–2005, great shearwaters being the most common species taken followed by common eider (Ellis et al., in press). In the Gulf of St. Lawrence annual take of 367 birds (range 11–1787) was estimated during 2001–2008 with common guillemots dominating the bycatch composition (Ellis et al., in press).

3.3.3. USA NW Atlantic Coast

Observer data collected by the US Northeast Fisheries Science Center have been analysed by Lanza and Griffin (1997) (1989–1993 data) and Soczek (2006) (1994–2003 data). Shearwaters were the most commonly caught group of birds (81% of birds killed), while other species included gulls, loons, auks, gannets and fulmars (Soczek, 2006). Soczek (2006) estimated 1000–3000 birds caught annually from 1994–1999, dropping to fewer than 500 individuals from 2000–2003 in the Gulf of Maine and southern New England. The decrease in the later period is suggested to reflect lower number of birds foraging in the region due to decreased ocean productivity as a result of the negative phase of the North Atlantic Oscillation (Soczek, 2006).

Further south, using beached bird surveys and counts of coastal gillnets, Forsell (1999) estimated 2387 birds killed on the US Atlantic coast between New Jersey to North Carolina, the most common victims being common loons (*Gavia immer*) and red-throated loons, and warned about potentially unsustainable levels of bycatch.

Warden (2010) assessed overall loon bycatch in the US Atlantic waters and, by analysing gillnet fisheries observer data from 1997 to 2006, estimated that 551 common loons and 897 red-throated loons were killed per year in the area between Maine and North Carolina. By applying a potential biological removal measure the author found that bycatch of red-throated loons is of potential conservation concern (Warden, 2010).

Thus, overall bird bycatch in gillnets does not seem very high in the USA NW Atlantic region, but, as pointed out by Forsell (1999) and Warden (2010), mortality of red-throated loons in coastal gillnets might be unsustainable.

3.4. Southwest Atlantic

This region includes Atlantic waters off the coast of Brazil, Uruguay and Argentina (Fig. 1). Productive waters support a relatively high diversity and abundance of diving seabirds, including shearwaters, petrels, cormorants and penguins.

Data on gillnet bycatch are sparse in the SW Atlantic region. The deep-water gillnet fishery targeting monkfish (*Lophius gastrophysus*) off the coast of southern Brazil was estimated to kill 802 birds in 2001 (Perez and Wahrlich, 2005). While the majority of birds were not identified to species, those identified included white-chinned petrels (*Procellaria aequinoctialis*), great shearwaters and Cape petrels (*Daption capensis*). White-chinned petrels, spectacled petrels (*Procellaria conspicillata*), and southern fulmars (*Fulmarus glacialoides*) have also been recorded caught in gillnets along the Santa Catarina coast of Brazil (Neves et al., 2006).

In addition, Cardoso et al. (2011) reported very high bycatch rates of Magellanic penguins (*Spheniscus magellanicus*) in driftnet and bottom gillnet fisheries off the coast of southern Brazil. The authors reported 68 penguins killed in 17 gillnet sets during eight fishing days, while the entire fleet consists of 280 vessels and the fishing season lasts from July to October (Cardoso et al., 2011). Therefore, overall bycatch may number hundreds or even thousands of penguins killed annually, and Cardoso et al. (2011) suggested that the impact on Magellanic penguin populations is probably significant.

3.5. Northeast Pacific

This region, which includes coastal and offshore waters of the US and Canada (Fig. 1), is renowned for its high diversity and abundance of diving birds, especially in high latitudes. Auks are especially diverse and numerous, and coastal waters are used by nonbreeding seaducks, loons and resident cormorants. The region is also visited by millions of migratory shearwaters from the southern hemisphere.

Gillnetting has been present on the Californian coast since at least the 1930s (DeGange et al., 1993). During the 1970s and 1980s, fishing effort increased along with the introduction of monofilament nets, and so did seabird bycatch, particularly of common guillemot. Colonies of this species declined rapidly

(DeGange et al., 1993). Later Julian and Beeson (1998) continued to find substantial bycatch in gillnet fisheries off California. Forney et al. (2001) estimated that common guillemot mortality in 1995–1998 ranged between 5918 and 13,060 birds killed per year in the Californian halibut gillnet fishery alone. During the 1980s, a series of regulations were put in place, and by 2000 a closure to gillnets in depths <60 fathoms was enforced along the entire coast of central California. Following this fishing restriction, only 1 common guillemot and 60 Brandt's cormorants (*Phalacrocorax penicillatus*) were estimated to be killed in the halibut fishery in 2003 (Carretta and Chivers, 2004). Carretta and Chivers (2004) also reported only low bycatch of seabirds in the California drift gillnet fishery for swordfish (*Xiphias gladius*) and thresher shark (*Alopias vulpinus*): in 1996–2002 only 19 birds were estimated killed in that period, 13 of them northern fulmars. Today some gillnetting continues in California, but common guillemot populations have since recovered (McChesney et al., 2009).

Further north, common guillemot remains the species most frequently caught in coastal gillnets in Washington State and British Columbia. Hamel et al. (2009) assessed marine bird strandings in the Salish Sea area and found that common guillemot carcass records were frequently associated with bycatch, and that such mortality added 0.2–2.9% to annual mortality rates. In Puget Sound, 109 birds, mostly common guillemots, were recorded caught in non-tribal salmon fishery in 1993 by monitoring 606 sets or about 1.5% of fishing effort (Pierce et al., 1994). Similarly, Beattie and Lutz (1994) found that common guillemots and rhinoceros auklets (*Cerorhinca monocerata*) frequently entangle in salmon nets of tribal fisheries: 128 birds were recorded in 184 observed sets. Due to declining salmon stocks fishing effort has been decreasing in Washington State in both tribal and non-tribal fisheries – 5 to 10-fold between the 1980s and the late 1990s (McShane et al., 2004). The risk of bycatch of marbled murrelets (*Brachyramphus marmoratus*) prompted introduction of fisheries regulations to reduce bycatch in Puget Sound starting from 1999, but these regulations affected only state-regulated fisheries and were not immediately adopted by tribal fisheries nor fisheries in neighbouring British Columbia (Harrison, 2001). We found no information about levels of compliance since then.

Similarly, in the assessment of seabird bycatch in British Columbia, Smith and Morgan (2005) found that common guillemots were the most frequent victim in salmon gillnet fisheries. The authors estimated that on average 12,085 seabirds were caught annually during 1995–2001, 69% being common guillemots, 23% rhinoceros auklets, and lower numbers of marbled murrelets, sooty shearwaters (*Puffinus griseus*), pelagic cormorants (*Phalacrocorax pelagicus*), pigeon guillemots (*Cepphus columba*), common loons, pacific loons (*Gavia pacifica*), Brandt's cormorants and Cassin's auklets (*Ptychoramphus aleuticus*) (Smith and Morgan, 2005).

The declining marbled murrelet has been extensively studied along the west coast of North America. Due to reduced fishing effort and fisheries restrictions gillnet mortality has decreased recently in California, Oregon and Washington compared to bycatch in the 1980s and 1990s and latest gillnet mortality levels are not considered responsible for the continuing population declines (McShane et al., 2004). Through extensive review of population status and threats Piatt et al. (2007) concluded that annual bycatch mortality or marbled murrelets is "likely in the low thousands per year" in British Columbia and Alaska. Further, authors suggested that bycatch along with oil pollution and competition with fisheries is unlikely to account for the observed population decline alone (Piatt et al., 2007).

In Alaska, bycatch data are sparse, but auks are reported as the most frequently caught species. The Kodiak Island salmon set gillnet fishery was estimated to kill 528 birds in 2002 and 1097 in 2005, the most common species being common guillemot, tufted puffin (*Fratercula cirrhata*), pigeon guillemot, marbled murrelet, red-faced cormorant (*Phalacrocorax urile*), pelagic cormorant and lower numbers of others (Manly, 2007). The Yakutat salmon setnet fishery was estimated to kill 305 birds in 2007 and 137 in 2008, the most common species being marbled murrelet, common guillemot and loons (Manly, 2009). In salmon fisheries in Cook Inlet, 1739 birds were estimated caught in 1999 and 107 in 2000; confidence intervals of these estimates, however, are large (Manly, 2006).

Overall, the bycatch mortality of seabirds along the Pacific coast of US and Canada has declined following enacted fishery regulations and reduced fishing effort (McShane et al., 2004; Piatt et al., 2007), and by summing latest available estimates we are guessing that about 20,000 birds are caught in gillnets per year. However, relatively little information is available from Alaska where seabird diversity and abundance are very high and therefore there is a potential conflict with extensive gillnet fisheries (Piatt et al., 2007). Nitta and Henderson (1993) reviewed interactions between Hawaiian fisheries and protected species, but found no seabirds among bycatch of small-scale coastal gillnet fisheries.

3.6. Northwest Pacific

This region encompasses northwestern waters of the Pacific Ocean bordering China, Russia, Japan and the western half of the Aleutian chain (Fig. 1). The region is distinguished by exceptionally high diversity and abundance of diving birds, including auks, seaducks, loons, grebes, cormorants and shearwaters.

Use of driftnets in the Northwest Pacific was introduced by the Japanese in the 1920s (Artukhin et al., 2010). Monitoring of seabird bycatch was initiated by American and Japanese observers in the 1970s when it was estimated that hundreds of thousands of birds were dying annually in the region (Ainley et al., 1981; Ogi, 1984; DeGange and Day, 1991; Artukhin et al., 2010). Driftnet fisheries in the US EEZ and high seas ceased after 1991, following the UN ban on large-scale driftnet fishing in the high seas.

Since the early 1990s, Russia allowed the Japanese driftnet fleet to fish salmon in the Russian EEZ. Between 1993–2001 fisheries observers collected bycatch data, with results summarised by Spiridonov and Nikolaeva (2004) and updated by Artukhin et al. (2010). Bycatch by the Russian driftnet fleet fishing in the same region was also reported for the period 1996–2005 (Artukhin et al., 2010).

Between 1993–2001, 183,646 birds of 31 species were collected as bycatch in the Japanese fleet, auks constituting over 60% and shearwaters over 30% of all birds, with the thick-billed guillemot and short-tailed shearwater (*Puffinus tenuirostris*) being the main victims in each category. The estimated annual bycatch of seabirds in this fishery was 94,330 (CI 70,183–118,478) (Artukhin et al., 2010).

Additionally, 18,689 birds of 20 species were collected from the Russian fleet between 1996 and 2005. Shearwaters, mostly short-tailed shearwater, were most frequently caught (34.8%), followed by tufted puffins (28.7%), guillemots (18.3%), crested auklets (*Aethia cristatella*, 6.9%) and northern fulmars (5.2%). The estimated average bycatch was 46,099 birds per year (CI 39,254–52,944) (Artukhin et al., 2010).

Despite the very high bycatch of short-tailed shearwater, northern fulmar and crested auklet, Artukhin et al. (2010) concluded that this mortality was not affecting the very large global populations of these species, although it should be noted that little is known about their population trends. However, the authors suggested that bycatch was posing a significant threat to thick-billed guillemot colonies in the southwestern Bering Sea and Pacific coast of southwestern Kamchatka and that local colonies of tufted puffins could be similarly affected (Artukhin et al., 2010). Furthermore, the authors recorded instances of threatened species also being killed, such as the yellow-billed loon (*Gavia adamsii*), short-tailed albatross (*Phoebastria albatrus*), red-legged kittiwake (*Rissa brevirostris*), and long-billed and Kittlitz's murrelets (*Brachyramphus perdix* and *B. brevirostris*).

In Japan, Ogi (1984) also highlighted tufted puffin as a species of conservation concern due to gillnet fishing. Ogi (2008) linked declines of Japanese murrelet (*Synthliboramphus wumizusume*), common guillemot, tufted puffin and spectacled guillemot (*Cepphus carbo*) to the impact of gillnet fisheries. Of these, the Japanese murrelet is a National monument in Japan (Hasegawa, 1984) and listed as Vulnerable on the IUCN red list. Bycatch of this species had been recorded in high sea driftnet fisheries prior to 1991 (Piatt and Gould, 1994), and it is thought that ongoing gillnet fisheries in the Japanese EEZ continue to catch this species, with the fishery including thousands of small boats (DeGange et al., 1993). However, we did not find any data to give an annual bycatch estimate in the EEZ of Japan, around the Korean Peninsula and eastern China.

3.7. Southwest Pacific

The Southwest Pacific includes waters around New Zealand and southwestern Australia (Fig. 1), and supports a high diversity of seabirds susceptible to bycatch in gillnets, including many species of penguins, cormorants, shearwaters and petrels (Taylor, 2000a,b).

Taylor (2000a,b) identified mortality in inshore commercial and recreational gillnet fisheries as an existing or potential threat to a number of penguin, cormorant and shearwater species in New Zealand, although overall scale of bycatch and impacts on local seabird populations remain generally unknown. Darby and Dawson (2000) studied yellow-eyed penguin (*Megadyptes antipodes*) and concluded that bycatch in gillnets is likely impacting the small population of this species. Ellenberg and Mattern (2012) also concluded that setnet bycatch of yellow-eyed penguin may be substantial, but that there was still insufficient information to assess fisheries impact. In relation to other species, Lalas (1993) investigated bycatch of shags in recreational net fisheries in Otago Harbour, and concluded that impact on local populations of little pied cormorant (*Phalacrocorax melanoleucos*) and Stewart Island shag (*Phalacrocorax chalconotus*) was low, but a potential threat to the local spotted shag (*Phalacrocorax punctatus*) population (Lalas, 1993). More recently, observer data from 2008–2010 recorded yellow-eyed penguin, Fiordland penguin (*Eudyptes pachyrhynchus*), Cape petrel and 3 species of shags killed in New Zealand inshore setnet fisheries, and additional species (including albatrosses and petrels), caught but released alive (Ramm, 2010, 2012). No estimate of total annual bycatch was given.

Similarly, little is known about extent of seabird mortality in gillnet fisheries in Australian waters. Norman (2000) reported results of a mail survey of fishermen in southern Australia, which suggested that little penguins (*Eudyptula minor*) and cormorants die in gillnets, although in low numbers. Stevenson and Woehler (2007) also identified recreational gillnets as one of the causes of little penguin population decline in Tasmania. These authors note that unattended and overnight recreational gillnetting was banned in coastal waters of Tasmania since 2004, which may have reduced numbers being killed.

More recently, Spain reported to the new South Pacific Regional Fisheries Management Organisation that it had two deep water gillnet vessels operating in the Tasman Sea in 2009–2010. No bycatch data were made available (SPRFMO, 2009).

3.8. Southeast Pacific

The Southeast Pacific (Fig. 1) is a very productive region, however the diversity of diving seabirds is relatively low and limited to Magellanic and Humboldt penguins (*Spheniscus humboldti*), cormorants, boobies and shearwaters.

The scale of gillnet fishing in Chile and Peru goes largely unreported due to the extensive involvement of small artisanal vessels. In Chile, Simeone et al. (1999) estimated 120 Humboldt penguins caught each year in the ''corvina'' gillnet fishery between 1991–1996. Magellanic penguins were also caught, as well as red-legged cormorant (*Phalacrocorax gaimardi*) and guanay cormorant (*P. bougainvillii*). Wallace et al. (1999) reported that 8 out of 19 ring recoveries of Humboldt penguins came from net entanglements in central Chile in the mid-1990s.

In Peru, a study in the 1990s also found Humboldt penguin making up >50% of all seabird bycatch (Majluf et al., 2002). More recently, 49 seabirds were caught in 914 observed sets, including 12 white-chinned petrels, 14 guanay cormorants, 4 Humboldt penguins, 6 sooty shearwaters, 4 pink-footed shearwaters (*Puffinus creatopus*) and low numbers of waved albatross (*Phoebastria irrorata*), black-browed albatrosses (*Thalassarche melanophris*) and grey-headed albatross (*Thalassarche chrysostoma)* (Mangel et al., 2011). Considering the very large Peruvian gillnet fleet, the authors suggested that annual bycatch likely exceeds 10,000 birds (Mangel et al., 2011). Fishermen questionnaires have indicated that Peruvian boobies (*Sula variegata*) also become entangled in gillnets (Ayala, 2008). In addition to incidental bycatch it is thought that Peruvian gillnet fishers may intentionally catch waved albatrosses for food (Awkerman et al., 2006; Ayala, 2008).

No seabird bycatch was recorded when observing 165 sets of driftnet fishery in Ecuador in 2008–2011 (Mangel et al., 2011).

Though information on seabird bycatch in gillnet fisheries is rather limited in this region, reports of consistent bycatch of Humboldt penguins suggest that fisheries induced mortality of this Vulnerable species might be unsustainable. The intentional or unintentional bycatch of the Critically Endangered waved albatrosses is also clearly unacceptable. The magnitude and significance of bycatch of several other threatened species of seabirds remain unknown.

3.9. Southeast Atlantic

The Southeast Atlantic features the productive region of the Benguela Current, which is home to several locally abundant diving seabird populations, including African penguin (*Spheniscus demersus*), Cape gannet (*Morus capensis*), shearwaters and petrels. No information about seabird bycatch in gillnets is available from the region.

3.10. Caribbean

Few diving seabird species inhabit the Caribbean region, and no seabird bycatch in gillnets has been reported.

3.11. Indian Ocean

The diversity and abundance of diving seabirds is low in the region. Reports are numerous of sea turtles and marine mammals caught in gillnets along the coasts of Southeast Asia and Africa, but there are no records of seabird bycatch. It is believed that Socotra cormorants (*Phalacrocorax nigrogularis*) are caught in gillnets (Waugh et al., 2011); however we found no studies documenting that.

3.12. Tropical Pacific

The Tropical Pacific region includes tropical and subtropical regions of the Pacific Ocean, ranging from Mexico to Colombia in the East, and from Taiwan to northeast Australia in the West (Fig. 1).

The few seabird species that are susceptible to bycatch in gillnet fisheries in this region include boobies, cormorants and migrating shearwaters. No information about seabird bycatch in gillnets is available from the Tropical Pacific.

3.13. Southern Ocean

The Southern Ocean is home to very numerous populations of penguins, petrels and shearwaters. No gillnet fishing takes place in this region.

4. Knowledge gaps

In general, knowledge of seabird bycatch in gillnet fisheries is highly fragmented. Even from regions where numerous reports are available, e.g. the Baltic Sea, information often originates from short-term studies and opportunistic observations. Bird bycatch in gillnets is rarely the subject of systematic and continuous monitoring. Better knowledge is needed from every region where seabird bycatch is known or could be anticipated.

However, several regions can be identified as being especially information deficient and where presence of both susceptible species and gillnet fisheries implies potential existence of high seabird bycatch. The Japanese and Korean EEZs in the Northwest Pacific represent two such areas. The Southeast Atlantic is another region, where seabird bycatch must be suspected along coasts of South Africa and Namibia.

There are also regions where existing reports indicate that there could be a substantial bird bycatch, but no reliable estimates are available. Seabird mortality in small-scale fisheries off Chile remains unknown, as does total bycatch in gillnet fleets of Brazil and possibly other countries in the Southwest Atlantic. Also, no bycatch estimates exist for the Mediterranean Sea, New Zealand and Australian waters.

Lastly, almost no information is available on seabird bycatch in gillnets of tropical regions of all oceans. Although it is known that gillnet fisheries are prevalent along coasts of most tropical countries (Waugh et al., 2011), the low occurrence of susceptible seabird species in these areas allows us to presume no or little interaction with fisheries, but verification would be valuable.

5. Mitigation of seabird bycatch in gillnet fisheries

Several methods have been proposed for mitigating seabird bycatch in gillnet fisheries but few of these have been extensively developed or implemented (Bull, 2007).

5.1. Spatiotemporal closures

Many authors have considered spatiotemporal management of fishing effort as one of the most viable solutions for seabird bycatch mitigation in gillnet fisheries, which, when fine-tuned for local conditions, could allow coexistence of gillnet fisheries and seabirds. In Puget Sound, Melvin et al. (1999) showed that restriction of fisheries to the period of peak salmon abundance could reduce seabird bycatch whilst maintaining a good fish catch. Benjamins et al. (2008) highlighted that seasonal closure of the Newfoundland and Labrador lumpsucker fishery during the arrival of birds at their breeding colonies would be a useful mitigation tool.

5.2. Visual alerts

The introduction of monofilament netting has increased seabird bycatch rates as a result of reduced net visibility (DeGange et al., 1993). With experimental testing of modified gillnets for salmon in Puget Sound (USA), Melvin et al. (1999) found that increased visibility of the upper net panel reduced seabird bycatch by up to 45%.

However, increasing net visibility may have little effect for nocturnally diving seabirds, or species which come in contact with fishing gear in poor visibility conditions. It is likely that more visible nets may also reduce catches of target species.

5.3. Acoustic alerts

Acoustic pingers were initially developed to act as a warning device to reduce entanglement of marine mammals in gillnets. Melvin et al. (1999) tested pingers with a frequency within the generic audiogram of birds, and found that common guillemot bycatch was reduced by 50% while there was no effect on bycatch of rhinoceros auklets. In contrast however, higher bird bycatch rates were found in nets when pingers tuned to deterring marine mammals were used in Kodiak Island salmon fisheries (Manly, 2007). Further work is clearly needed to shed light on use of acoustic alerts.

5.4. Restrictions on fishing depth

The majority of diving birds prefer shallow waters and most seabird bycatch occurs in depths of less than 20 m (Stempniewicz, 1994). Bellebaum et al. (2013) also found that the probability of bycatch decreased with increasing water depth. In California, the ban on gillnetting in depths <60 fathoms has nearly eliminated formerly high bycatch of common guillemots (Carretta and Chivers, 2004). It was also found that submerging driftnets at 2 m below the surface significantly reduced seabird bycatch in the northern Pacific (Hayase and Yatsu, 1993). According to these findings, regulating the depths at which gillnetting occurs could substantially reduce bird mortalities. Consideration would need to be given to the impacts that this would have on fish catch rates.

5.5. Change of fishing gear

An alternative approach is to switch from gillnets to other fishing gears. Often there are alternative means to catch target fish species, some of which may also be viable from a practical and economic perspective.

In the German Baltic Sea, replacing gillnets with longlines has been proposed as a means to decrease seaduck bycatch: per tonne of landed cod, bird bycatch was approximately three times lower for longlines compared to gillnets (Mentjes and Gabriel, 1999; Bellebaum et al., 2013). Similarly, in the eastern Baltic it has been suggested that a switch to longlines would nearly eliminate bycatch of birds and offer a viable alternative for cod fishing, and possibly salmon (Vetemaa and Ložys, 2009). Virtually no bird bycatch was recorded during experimental fishing with baited pots for cod in the German sector of the Baltic Sea, while birds were caught in standard gillnets nearby (Bellebaum et al., 2013). Based on the experience of Latvian fishermen, fish traps for herring and other fish were introduced in Lithuania, and proved to be more efficient in catching fish compared to traditionally used gillnets while at the same time having no bycatch of birds (Vetemaa and Ložys, 2009).

However, in some circumstances switching to alternative fishing gear may increase mortalities of other species or have other undesirable effects on marine ecosystems.

6. Discussion

A simple summing of the most recent bycatch estimates from regions around the world suggests that nearly 400,000 seabirds die in gillnet fisheries every year (Table 2). Information about

Table 2
Cumulative most recent estimates of annual bird bycatch in gillnet fisheries in different regions of the world, possibly significantly affected species and responsible fisheries (see references in chapter 3). Bycatch estimates given in parentheses indicate numbers for sub-regions.

Region/sub-regions	Estimated total annual bycatch	Period of study	Significantly affected species	Main fisheries
1. Northeast Atlantic	>194,000			
Baltic Sea	*(76,000)*	1980–2009	Long-tailed duck, Steller's eider, greater scaup	Small-scale nearshore set net and driftnet fisheries
Norwegian Sea	*(8 000)*	2009–2010	–	Small-scale fleet of vessels shorter than 15 m (using gillnets and longlines)
North Sea and Atlantic	*(>10,000)*	1990–2002	Common guillemot (population at the Atlantic coast of Portugal)	Small-scale coastal gillnet fisheries
Iceland	*(100,000)*			Gillnet fisheries for lumpsucker
2. Northwest Atlantic	>30,000			
West Greenland	*(10,000–20,000)*	2003–2008	–	Gillnet fisheries for lumpsucker
Atlantic Canada	*(8000 – 15,000)*	2000–2008	–	Nearshore and offshore gillnet fisheries for cod, lumpsucker, monkfish/skates, flounder and Greenland halibut
USA NW Atlantic coast	*(2000)*	1997–2006	Red-throated loon	Coastal gillnet fisheries
3. Southwest Atlantic	>>1000	2001–2009	Magellanic penguin	Various set net and driftnet fisheries
4. Northeast Pacific	20,000	1993–2002	Local colonies of common guillemot	
5. Northwest Pacific	140,000	1993–2005	Local colonies of thick-billed guillemot and tufted puffin	Gillnet fisheries for salmon
6. Southwest Pacific	Unknown		Yellow-eyed penguin	Various commercial and recreational gillnet fisheries
7. Southeast Pacific	>10,000	2005–2011	Humboldt penguin, waved albatross	Small-scale set net and driftnet fisheries

bycatch which is known as discontinued was not included in this estimate. The approaches used to collect data and estimate total bycatch varied greatly. Information was collected using onboard observers, cooperating fishermen, questionnaires, ring recoveries, stranded bird surveys and opportunistic observations. Estimates of the overall magnitude of the issue were obtained using models, extrapolations or simply best guesses. Metrics used to measure fishing effort and bird bycatch also differed among studies. Therefore, available estimates have varying levels of uncertainty. Nevertheless, these figures represent the best available information. It is also almost certain that the actual number of birds being killed in gillnets is much higher, as bycatch estimates were unavailable for several regions, some data collection methods (e.g. fisherman questionnaires) tend to underestimate mortality (NMFS, 2004), some birds drop out of the net or are scavenged before being accounted for, and finally there is a lot of lost fishing gear in world oceans ("ghost nets"), which continue to kill birds and other animals (Laist, 1997; Good et al., 2009). Thus, 400,000 birds dying in gillnets should be viewed as a minimum annual estimate. The cumulative estimate of bird bycatch in gillnets likely exceeds seabird mortality in longline fisheries, which was estimated to be at least 160,000, and potentially over 320,000, birds per year (Anderson et al., 2011).

When assessing seabird bycatch in gillnet fisheries, many authors suggested that gillnets were a contributing factor to population declines or a main cause decimating local colonies (summarised in Table 2). Most often, impacts were based on correlative comparison of population trends and fisheries bycatch or other factors. However, several studies used a potential biological removal approach (Žydelis et al., 2009; Warden, 2010). Population models have only been used to analyse gillnet impacts on data from the Atlantic Iberian coast (Velando and Freire, 2002; Munilla et al., 2007), and in both cases a significant impact was identified.

Gillnet mortality affects a largely different suite of seabird species compared to bycatch in longline and trawl fisheries: it is primarily pursuit diving and benthic feeding birds that drown in gillnets. However, shearwaters, fulmars and *Procellaria* petrels are regularly recorded as bycatch in all gear types, therefore, cumulative impacts from different fisheries should be considered when assessing fisheries interactions with these species (e.g. Uhlmann, 2003).

Thus far there are no technological solutions known that universally mitigate seabird bycatch in gillnets. This is partly due to the large variety of gillnet configurations, and the high diversity of target fish species and affected seabirds, but it also reflects modest investment in mitigation research to date. Based on existing mitigation trials, it is also apparent that mitigation means may be highly site-specific in some cases. It should also be recognised that worldwide there has been little concerted action to address seabird bycatch in gillnet fisheries so far.

In some regions seabird bycatch in gillnets co-occurs with bycatch of seaturtles and marine mammals (e.g. SE Pacific, SW Atlantic; Read, 2008; Wallace et al., 2010); thus collaborative efforts with specialists investigating other taxa would help monitor fisheries impacts and planning conservation actions and mitigation.

7. Conclusions

By reviewing available data on seabird bycatch in gillnet fisheries we derived an annual minimum mortality estimate of 400,000 birds. Based on foraging behaviour we evaluated that 148 seabird species are potentially susceptible to bycatch in gillnets. Of those, 81 species have been reported caught and additionally 23 surface-foraging species, which we assumed as unsusceptible were recorded caught in fishing nets.

Auks represent the taxonomic group (family *Alcidae*) that is most frequently caught. Significant impacts of gillnet mortality have been identified for local colonies of auks off the Atlantic Iberian coast and islands in the Northwest Pacific. Significant or potentially significant impacts have also been identified for seaducks in the Baltic Sea, loons in the Northwest Atlantic and penguins in the Southeast Pacific, Southwest Atlantic and New Zealand.

Seabird bycatch in gillnets is most prevalent in the temperate to sub-polar regions of both hemispheres, and has been rarely recorded in the tropics. This spatial pattern is largely determined by the distribution of susceptible species.

In addition we identified several regions where seabird bycatch in gillnet fisheries may be occurring, but data are non-existent or very scarce. These included the EEZs of Japan and Koreas, Southwest Pacific, Chilean waters in the Southeast Pacific, Southeast and Southwest Atlantic, and the Mediterranean Sea.

To date, the most feasible way to mitigate bycatch in gillnets has been through spatial and temporal regulation of fishing effort or gear substitution. In comparison to longline and trawl fisheries, research into technical bycatch mitigation measures for seabird bycatch in gillnet fisheries has been very limited. Existing research has pointed to several potential solutions, such as increasing visibility of nets, but further research is needed.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2013.04.002.

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