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Review

Threats to seabirds: A global assessment

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ABSTRACT

We present the first objective quantitative assessment of the threats to all 359 species of seabirds, identify the main challenges facing them, and outline priority actions for their conservation. We applied the standardised Threats Classification Scheme developed for the IUCN Red List to objectively assess threats to each species and analysed the data according to global IUCN threat status, taxonomic group, and primary foraging habitat (coastal or pelagic). The top three threats to seabirds in terms of number of species affected and average impact are: invasive alien species, affecting 165 species across all the most threatened groups; bycatch in fisheries, affecting fewer species (100) but with the greatest average impact; and climate change/severe weather, affecting 96 species. Overfishing, hunting/trapping and disturbance were also identified as major threats to seabirds. Reversing the top three threats alone would benefit two-thirds of all species and c. 380 million individual seabirds (c. 45% of the total global seabird population). Most seabirds (c. 70%), especially globally threatened species, face multiple threats. For albatrosses, petrels and penguins in particular (the three most threatened groups of seabirds), it is essential to tackle both terrestrial and marine threats to reverse declines. As the negative effects of climate change are harder to mitigate, it is vital to compensate by addressing other major threats that often affect the same species, such as invasive alien species, bycatch and overfishing, for which proven solutions exist.

1. Introduction

Seabirds are one of the most threatened groups of birds (Croxall et al., 2012; BirdLife International, 2018). They are also regarded as good indicators of the health of marine ecosystems (Piatt and Sydeman, 2007; Parsons et al., 2008), and have a key role in marine ecosystems, with an overall consumption of biomass of the same order of magnitude as global fisheries landings (Brooke, 2004; Cury et al., 2011). They occur across all oceans, from coastal areas to the high seas, and are easier to study than most other marine animals because they are readily visible at sea and depend on land to breed, allowing for a better understanding of their population trends and of their threats.

The latest assessment of the global threat status of seabirds, using the International Union for Conservation of Nature (IUCN) Red List criteria, revealed that 31% of all seabird species are globally threatened (i.e. Critically Endangered, Endangered or Vulnerable; 110 of 359 species), and another 11% (40 species) are Near Threatened (NT) (BirdLife International, 2018; Fig. A1, Appendix 3). Additionally, almost half of all species (47%) have declining population trends (BirdLife International, 2019).

Some of the drivers of these declines are threats faced at the colonies, such as invasive alien species (Spatz et al., 2014, 2017), whereas others operate at sea, including incidental mortality (bycatch) in fisheries, and overfishing (Žydelis et al., 2009; Anderson et al., 2011; Grémillet et al., 2018). Well-documented cases of bycatch as a threat driving severe declines in seabird populations include those of albatross species, with long-term studies conducted at South Georgia in the south Atlantic Ocean identifying bycatch in longline or trawl fisheries as the primary cause of the 40–60% population declines observed over the last 35 years (Pardo et al., 2017). Bycatch is also identified as a key threat to the Balearic Shearwater *Puffinus mauretanicus* (Arcos, 2011). Species of small petrels such as Mascarene Petrel *Pseudobulweria aterrima* and Fiji

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Petrel *Pseudobulweria macgillivrayi* are on the brink of extinction due to predation by introduced mammals at their breeding colonies (Riethmuller et al., 2012; Rodríguez et al., 2019), and some are already possibly extinct (e.g. Jamaican Petrel *Pterodroma caribbaea*, Guadalupe Storm-petrel *Hydrobates macrodactylus*; Tobias et al., 2006). Depletion of food resources around seabird colonies due to intense fishing or changes in oceanographic conditions has also resulted in population declines of the African Penguin *Spheniscus demersus* in the Benguela Current region (Pichegru et al., 2009), of the Black-legged Kittiwake *Rissa tridactyla* in the North Sea (Carroll et al., 2017) and of several species in the area of the Humboldt Current (Barbraud et al., 2018).

Most previous reviews of threats to seabirds have focused on the causes of declines of specific groups, e.g. albatrosses (Phillips et al., 2016), petrels (Rodríguez et al., 2019), penguins (Borboroglu and Boersma, 2013; Trathan et al., 2015), or on the impact of a single threat, e.g. longline or gillnet bycatch (Anderson et al., 2011; Žydelis et al., 2009). The only global review to date was based on data up to 2010 and focused only on globally threatened seabirds (Croxall et al., 2012). However, to understand the conservation status of this group worldwide, it is important to assess the anthropogenic and natural pressures affecting all species, since many relatively abundant and widespread species of Least Concern on the IUCN Red List are now also in decline (e.g. Little Auk *Alle alle*, Fort et al., 2013; Chinstrap Penguin *Pygoscelis antarcticus*, Korczak-Abshire et al., 2012; Arctic Tern *Sterna paradisaea*, Burnham et al., 2017).

We present the results of the first quantitative review of the threats affecting all seabird species globally. We used data from > 900 publications and a standardised assessment approach (the IUCN Red List Threats Classification Scheme; IUCN, 2012; Salafsky et al., 2008), aiming to: a) identify the main ongoing drivers of population declines of seabirds globally; b) provide the first systematic appraisal of the overall impacts of each threat on multiple species; c) quantify the number of individual seabirds exposed to each threat; and d) highlight some of the challenges and priority actions needed and to improve the conservation status of seabirds.

2. Materials and methods

2.1. Selection and categorisation of species

We followed the taxonomy used by BirdLife International for the IUCN Red List (del Hoyo et al., 2014; BirdLife International, 2019) and considered seabirds to be those species for which a large proportion of the population rely on the marine environment for at least part of the year (Croxall et al., 2012). This criterion was met by 359 extant species (list available in Appendix 1). We grouped species based on taxonomy: albatrosses; large petrels and shearwaters; gadfly petrels (genera *Pterodroma* and *Pseudobulweria*); storm-petrels; other small petrels; penguins; auks; skuas; terns; gulls; frigatebirds and tropicbirds; gannets and boobies; cormorants and pelicans; sea ducks and allies; phalaropes (Appendix 1). We also split species into "pelagic" and "coastal" based on the definition provided by Croxall et al. (2012): "pelagic seabirds" are those that primarily use marine deep water (typically > 200 m in depth), or neritic, continental shelf water; and "coastal seabirds" are those that primarily use inshore waters (typically < 8 km from the shoreline; see Appendix 1). The global population trend of each species was also used in some analyses (using two categories: declining versus stable/increasing/unknown; BirdLife International, 2019).

2.2. Data sources and threats classification

For the first time, threats were systematically assessed for all 359 seabird species. We undertook a detailed review of the seabird threat data, held by BirdLife International, which are used to support the global status assessment of bird species for the IUCN Red List (BirdLife International, 2019), and the consistency of threat scoring between species was rigorously checked. We collected data through a combination of expert consultation (in collaboration with the respective seabird IUCN Species Survival Commission (SSC) Specialist Groups) and a comprehensive bibliographic search for studies reporting threats to each seabird species. In a first stage, we consulted summary species accounts published in the Handbook of the Birds of the World Alive (HBW Alive, 2018), supplemented by regional accounts from the Birds of North America (BNA online, 2018), New Zealand Birds Online (NZ Birds Online, 2018) and the Australian Government Species Profile and Threats Database (Department of the Environment and Energy, 2018). Secondly, we conducted searches in Web of Knowledge and Google Scholar, first using the *species name* (scientific name and common name separately) + "threat", and then using the *species name* and each threat named in the results of the preceding search. For species listed under the Agreement on the Conservation of Albatrosses and Petrels (ACAP), the ACAP Secretariat and relevant working groups reviewed the revised threat codings, and for penguins, the IUCN SSC Penguin Specialist Group performed this role, allowing the incorporation of additional literature and unpublished data. Overall, information from over 900 publications (each referenced to the appropriate species in the factsheets available on the BirdLife Data Zone; BirdLife International, 2019) was used to revise the 'threats' texts that form part of the IUCN Red List factsheets and assessments (BirdLife International, 2019).

Threats were classified using the IUCN Red List Threats Classification Scheme version 3.2 (Salafsky et al., 2008; IUCN, 2012). This scheme defines threats as "the proximate human activities or processes that have impacted, are impacting, or may impact the status of the taxon being assessed. Direct threats are synonymous with sources of stress and proximate pressures" (IUCN, 2012). In other words, and in the context of this study, a threat is a human activity or other process that affects the current conservation status of a species by causing a population or range reduction.

Each threat was coded initially using the IUCN Red List Threats Classification Scheme, down to Level 3 (the most detailed classification level) where possible (IUCN, 2012). For each threat, we assessed: 1) timing (i.e. ongoing; past but likely to return; past and unlikely to return; future); 2) scope (i.e. the proportion of the total population

Table 1
System for scoring impact of threats (from Garnett et al., 2018). Values within parentheses represent the percentage of the total population affected (scope) and the known or likely rate of population decline caused by the threat over three generations (severity). Impact values are the average of the product of the extremes of scope and severity in each interval (mean [min (scope)*min (severity)/100, max (scope)*max (severity)/100]).

Scope/severity	Very rapid declines (> 30%)	Rapid declines [20–30%]	Slow but significant declines or causing/could cause fluctuations [5–20%]	Negligible declines (< 5%)
Whole (> 90%)	63 Very high	23.5 High	11.8 Medium	2.9 Low
Majority [50–90%]	51.6 Very high	17.9 High	9.7 Medium	2.4 Low
Minority (< 50%)	24.9 High	7.4 Medium	4.8 Medium	1.2 Low

affected: minority (< 50%); majority (50–90%); whole (> 90%)); and 3) severity (i.e. the rate of population decline caused by the threat within its scope: very rapid; rapid; slow but significant; negligible; causing/could cause fluctuations) (IUCN, 2012 and Table 1). Each threat at the most detailed level can be recorded only once against a species, with the exception of 'Invasive & other problematic species, genes & diseases', for which an entry for each problematic species is possible. As one threat can have different timing and severity across the range of a species, the following convention was applied: 'Ongoing' threats were prioritised over 'Future' threats, which were prioritised over 'Past' threats. Hence, a slow, ongoing reduction was coded in preference to a rapid, past reduction. Stresses, which are the mechanism by which a threat directly or indirectly impacts the species, such as species mortality or ecosystem degradation, were also recorded as part of the IUCN threat assessment approach (IUCN, 2012). Further relevant detail beyond that required for the IUCN assessment was also noted when available, in particular the type of fishing gear and the scale of the fishery (small versus large) associated with the impact of bycatch. Overall, this process resulted in the compilation of 1637 records of threats to 359 seabird species.

The IUCN Red List Threats Classification Scheme was developed to be applied across all species of plants, animals and fungi, and thus often lacks resolution when applied to a specific group. For example, bycatch and overfishing, two frequent threats to seabirds (Croxall et al., 2012), are allocated the same threat code under the IUCN scheme (Level 1 = Biological Resource Use, Level 2 = Fishing & harvesting aquatic resources, and Level 3 = Unintentional effects). We therefore refined the threats classification by splitting: 1) "Biological resource use" into: "Bycatch", "Overfishing", "Disturbance", "Hunting/trapping" and "Logging & wood harvesting"; 2) "Invasive and other problematic species, genes & diseases" into "Invasive alien species" and "Diseases"; 3) "Agriculture & aquaculture" into "Agriculture" and "Aquaculture"; and 4) "Light pollution" from "Pollution" (see Appendix 2 for a more detailed explanation). We assumed the same impact score of "bycatch" and "overfishing" for species affected by both ($n = 34$), as it was not possible to distinguish their relative impacts (see above). The final list of threats considered in the analyses (Table A2.1, Appendix 2) was thus a combination of the original IUCN Red List classification of Level 1 threats (IUCN, 2012), modified as indicated above (see also Table A2.2, Appendix 2).

2.3. Data analysis

All the analyses (except where noted otherwise) considered only threats that were coded to the timing category "ongoing", with a known and non-zero scope and severity. We also analysed the threats separately for "pelagic" and "coastal" species, and for specific groups of seabirds (see Section 2.1 above). For these latter analyses, we distinguished terrestrial threats (e.g. invasive alien species, disturbance at colonies) from marine threats (e.g. overfishing, bycatch). Climate change/severe weather was considered in a separate category (see Table A2.2, Appendix 2 for more details on threats classified as marine or terrestrial). We estimated the impact of each ongoing threat on each species by multiplying the mean scope (the proportion of the population affected; see Table 1) by the mean severity (Table 1; Garnett et al., 2018), and categorised these into four levels, from "low" to "very high" (Table 1). For threats with multiple coding per species (see above), we used the highest value of impact. We also calculated the overall impact of each threat by summing the impact scores across all species.

Finally, we estimated the total number of birds (T) exposed to each threat (i) by summing the product of the global abundance of each species affected by the threat, and the scope of the threat,

$$T_i = \sum_{sp=1}^{n} A_{sp} * S_{i,sp}$$

where A = abundance of species *sp*, S = scope of the threat *i* to species *sp*. The global abundance of each species was extracted from the IUCN Red List database (BirdLife International, 2019) by multiplying the number of mature individuals (available for 95% of the species) by 1.5, to account for the number of non-breeders in the population (Brooke, 2004). In order to address the uncertainty associated with this estimate (given the large range of most estimates of abundance and of the values of scope – see Table 1), we applied a bootstrap approach (1000 repetitions), by selecting random values within the intervals of abundance (i.e. between the minimum and maximum abundance) and scope (i.e. a random value between the minimum and maximum scope for each category – see Table 1) of each species, from which we derived a 95% confidence interval. These analyses were carried out separately for species classified as: 1) globally threatened; 2) Near Threatened and Least Concern with a declining trend and 3) Least Concern with a non-declining trend.

3. Results

3.1. Threats to all seabird species

Invasive alien species, bycatch, hunting/trapping, climate change/severe weather and disturbance are the ongoing threats affecting most seabird species, with each affecting more than a fifth of all species (Fig. 1 and Table 2). Pollution, overfishing and problematic native species also affect many seabird species (> 50 each; Fig. 1). Bycatch, invasive alien species, overfishing and climate change/severe weather are the threats causing highest impacts on average (Fig. 1 and Table 2). The impacts of hunting/trapping and disturbance are relatively low by comparison (Fig. 1 and Table 2); in contrast, diseases and natural system modifications have high impacts on the few species affected (15 and 10 species, respectively; Fig. 1). Invasive alien species have the highest overall impact (i.e. the sum of all impacts on all species affected by this threat), followed by bycatch and climate change/severe weather (Table 2).

We estimate that > 170 million individual birds (> 20% of all seabirds) are currently exposed to the individual impacts of bycatch, invasive alien species and climate change/severe weather (Fig. 2), and that together > 380 million (c. 45% of all seabirds) are exposed to at least one of these three threats.

Overall, 301 (84%) of the 359 seabird species are impacted by at least one ongoing threat. About 70% of these are affected by at least two threats and 46% by at least three threats ($n = 301$). On average, each seabird species is affected by three ongoing threats (2.85 ± 0.12, range = 1–11, $n = 301$).

3.2. Threats to globally threatened species

The 110 globally threatened seabird species are largely affected by the same threats highlighted above – invasive alien species, bycatch, climate change/severe weather, hunting/trapping and overfishing (Fig. 3 and Table 2; see also Fig. A2 in Appendix 3). Problematic native species are also a major threat for globally threatened species, both pelagic and coastal. Disturbance is the threat affecting most coastal species, along with hunting/trapping, although mainly with medium or low impact (Fig. 3).

3.3. Threats to Near Threatened and declining Least Concern species

Invasive alien species, climate change/severe weather, bycatch and hunting/trapping are also the threats affecting the highest number of Near Threatened (NT) and Least Concern (LC) species with a declining trend; each affects > 30% of the species in this group (Fig. A3 in Appendix 3).

The populations of these species comprise nearly half of all individual seabirds in the world (45%–47%); about half of birds exposed

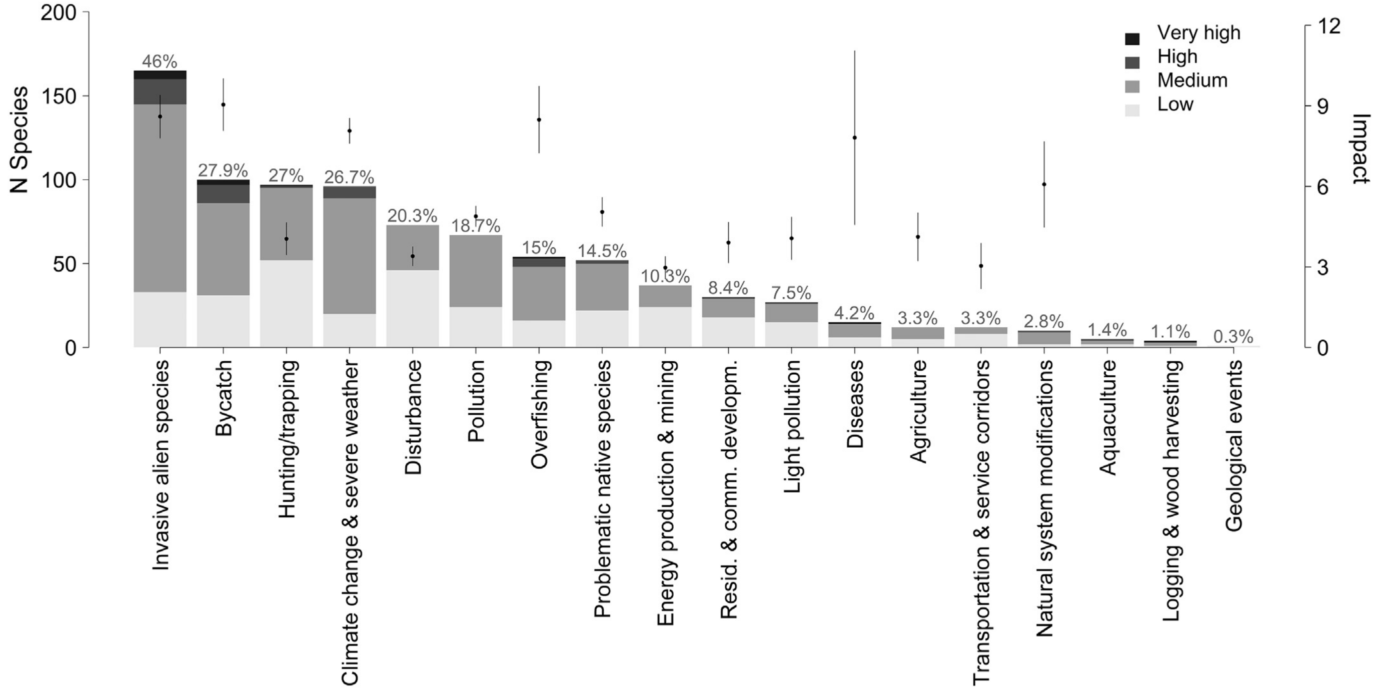

Fig. 1. Ongoing threats to all seabird species (ordered by the number of species affected). Left y axis: total number of species affected; Right y axis: average impact ± SE. Values atop bars indicate the percentage of species affected (n = 359).

to some of the major threats (especially bycatch, climate change/severe weather and invasive alien species) are NT and declining LC (Fig. 2); 81% of the species currently NT or LC with declining trends are impacted by at least one of these three threats.

3.4. *Threats to groups of seabirds*

The major threats to particular groups of highly threatened species are indicated in Fig. 4 (see also Fig. A4, Appendix 3, for the percentage of threatened species per group). Albatrosses are particularly affected by bycatch (90% of species). In addition, around half of albatross species (13 of 22) are affected by at least one terrestrial threat, mostly invasive alien species but also diseases, which have a high impact (Table 3), and over one-third are affected by climate change/severe weather.

More than 80% of penguin species are affected by climate change/severe weather (a higher proportion than any other seabird group). Marine threats such as overfishing, bycatch and pollution also have large impacts on several species of penguins (Fig. 4). The main threats at colonies are invasive alien species, problematic native species and disturbance, albeit with lower estimated impacts on average. Around half of the penguin species suffer medium, high or very high impacts from both marine and terrestrial threats (marine – pollution or overfishing; terrestrial – usually problematic native species; Table 3).

Invasive alien species and bycatch are also important threats for large petrels and shearwaters (eight species are affected by both these threats; Table 3), as is light pollution (Fig. 4). Cormorants and pelicans are also impacted by a combination of several terrestrial (including invasive alien species and problematic native species) and marine threats (bycatch, overfishing and pollution; Fig. 4 and Table 3). In contrast, gadfly petrels and storm-petrels are almost exclusively impacted by terrestrial threats, particularly by invasive alien species (and light pollution in the case of gadfly petrels; Fig. 4).

3.5. *Invasive alien species*

Rats *Rattus* spp. and cats *Felis catus* are the invasive alien species impacting the highest number of seabird species (> 100 and 90,

Table 2
Summary of the top threats (impacting > 20% of the species or having an high overall impact) affecting: all seabird species; only globally threatened species; only Near Threatened (NT) species and Least Concern (LC) species with declining trends. N species: number of species affected; N species main threat: number of species for which the threat is the main cause of decline (i.e. highest impact); Mean impact (± SE): mean impact on the species affected by the threat; Overall impact: sum of the impact scores across all species. Threats are listed in descending order of the overall impact on all species.

Threats	All species (n = 359)				Globally threatened species (n = 110)			NT and LC species (declining) (n = 119)		
	N species	N species main threat[a]	Mean impact	Overall impact	N species	Mean impact	Overall impact	N species	Mean impact	Overall impact
Invasive alien species	165	107	8.6 ± 0.8	1419.29	73	12.14 ± 1.64	885.89	62	6.12 ± 0.61	379.36
Bycatch	100	70	9.05 ± 0.97	904.66	50	11.78 ± 1.77	589.00	36	6.68 ± 0.75	240.62
Climate change/severe weather	96	63	8.07 ± 0.47	774.92	37	9.88 ± 0.80	365.53	43	7.44 ± 0.67	319.89
Overfishing	54	24[b]	8.49 ± 1.25	458.25	22	11.89 ± 2.81	261.49	19	6.79 ± 0.83	129.09
Hunting/trapping	97	38	4.05 ± 0.6	392.71	27	6.05 ± 1.98	163.37	35	4.03 ± 0.50	141.18
Disturbance	73	25	3.40 ± 0.36	248.31	26	4.23 ± 0.63	110.09	28	3.37 ± 0.57	94.36

[a] Some species can have more than one threat as the main cause of decline.
[b] Excluding species for which overfishing and bycatch are both indicated as the major threat.

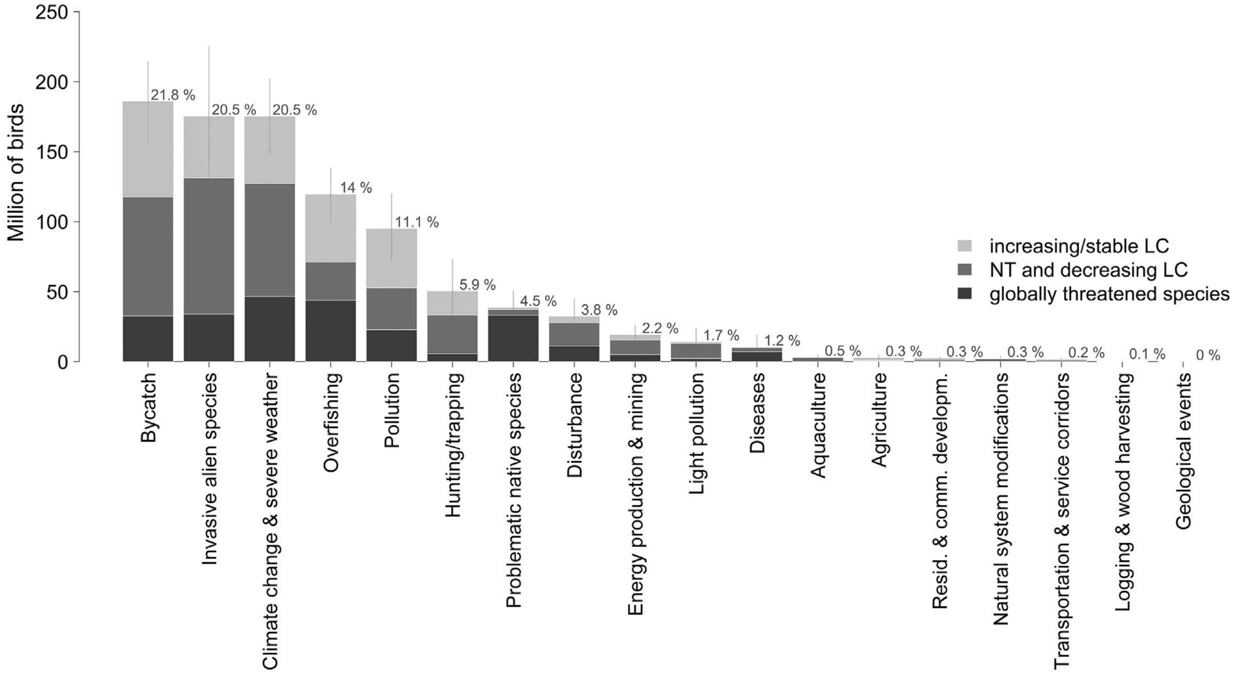

Fig. 2. Estimated total number of seabirds exposed to each threat. Error bars represent the 95% confidence intervals (see methods). Values atop bars indicate percentage of total number of seabirds affected.

respectively; Fig. 5). Sixty-three seabird species (38% of those affected by invasive alien species) are impacted by both rats and cats. Mice (*Mus* spp. and *Peromyscus maniculatus*) affect a smaller number of species (22, of which 20 are Procellariiformes - albatrosses, large petrels & shearwaters, gadfly petrels, prions and storm-petrels), but often with high severity.

3.6. Bycatch

Large-scale fisheries are causing declines of most species affected by bycatch (> 80), whereas < 40 species are affected by small-scale fisheries (Fig. 6). The average impacts (scope and severity) of large and small-scale fisheries are, however, similar (Fig. 6). Gillnet fisheries affect more species than longlining and trawl fisheries; these last two gear types have, however, a greater impact in terms of both average severity and scope (Fig. 6).

3.7. Climate change and severe weather

Climate change/severe weather impacts seabirds mostly due to habitat shifting and alteration, and temperature extremes (almost 40 species are affected by each of these threats, and with relatively high

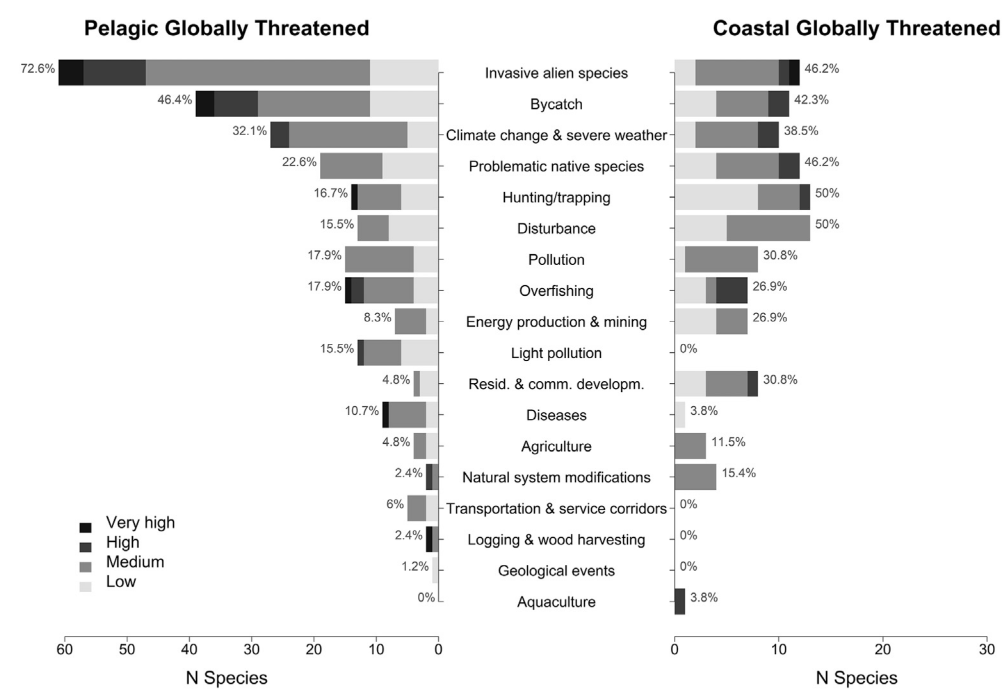

Fig. 3. Ongoing threats to pelagic (n = 84) and coastal (n = 26) globally threatened seabirds; values atop bars indicate percentage of species affected.

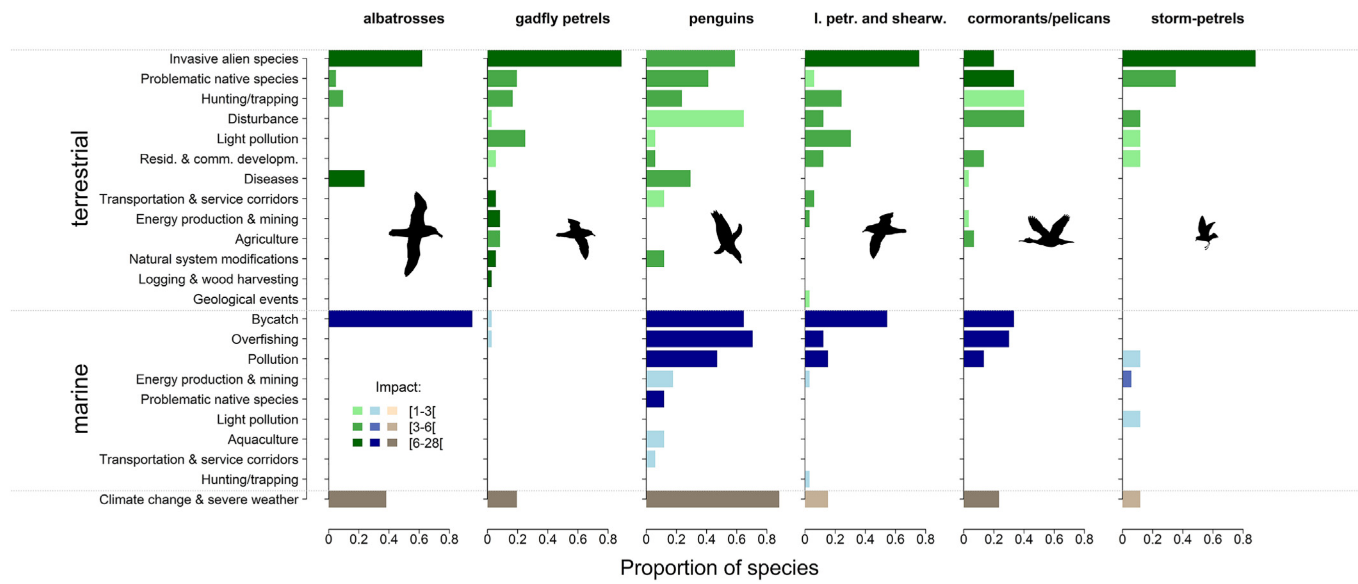

Fig. 4. Main threats (split into marine and terrestrial) by group of seabird species (only groups with > 30% of species classified as globally threatened are shown; see also Fig. A4 in Appendix 3). In column headings, *l. petr. and shearw.* = large petrels and shearwaters.

scope; Fig. 7). Storms/flooding impact > 20 species of seabirds, and with lower scope (Fig. 7).

Species impacted by climate change are also affected by three other threats on average (2.99 ± 0.2; mean ± SE), including invasive alien species (52%), bycatch (43%), and c. 30% by each of overfishing, hunting/trapping and/or pollution (Fig. A5, Appendix 3). For only 11% of seabird species is climate change/severe weather the only threat.

4. Discussion

This is the first comprehensive analysis to use consistent, objective criteria to assess the threats to all 359 seabird species worldwide. We found that invasive alien species, bycatch and climate change/severe weather are the top three threats to seabirds in terms of the number of species affected (165, 100 and 96, respectively; Fig. 1), overall impacts (Table 2), and the estimated total number of individual birds potentially affected (Fig. 2). Hunting/trapping and disturbance also affect many species (97 and 73, i.e. 27% and 20%, respectively), but with a low impact on average; conversely, overfishing has a relatively high impact on fewer species (54, i.e. 15%).

A comparison with the threat assessment made in 2010 is possible for globally threatened species (Croxall et al., 2012), despite minor changes in the list of species, and some differences in methods (e.g. checks for consistency in scoring threats across groups were not made in the previous study). Our results confirm the persistence of top threats such as invasive alien species and climate change/severe weather, which still affect a similar number of species (Fig. 8). Threats related to fishing have increased since the previous assessment, with bycatch now impacting 50 rather than 40, and overfishing 22 rather than 10 globally threatened species (Fig. 8). This is partly due to better understanding of the impacts of gillnet fisheries on seabirds (Žydelis et al., 2009; Crawford et al., 2017), especially coastal species such as sea ducks (Žydelis et al., 2009), including some species which have recently been uplisted to globally threatened (e.g. Long-tailed Duck *Clangula hyemalis*, Horned Grebe *Podiceps auritus*). The relevance of overfishing has also increased, both in pelagic and coastal species (e.g. penguins and cormorants; e.g. Crawford et al., 2015; Trathan et al., 2015). In contrast, the threat from marine pollution has decreased, now affecting 23 rather than 30 globally threatened species. The threat from pollution is largely related to oil spills, a well-known and conspicuous threat to seabirds during the 1970s and 1980s. Oil spill events has decreased greatly in recent decades (Roser, 2018), with a consequent predictable reduction

Table 3
Seabird groups affected by both terrestrial and marine threats (excluding the ones related to the climate change; see methods) with medium, high or very high impact[a], and most frequent interactions (only shown are those affecting > 2 species).

Group	N species with terrestrial and marine threats	Most frequent interactions terrestrial - marine	Number of species affected
Albatrosses	13 (59%)	Invasive alien species - bycatch	10
		Diseases - bycatch	3
Penguins	9 (50%)	Problematic native species - pollution	4
		Invasive alien species - pollution	3
		Problematic native species - overfishing	3
		Hunting/trapping - pollution	3
Auks	11 (46%)	Invasive alien species - pollution	6
		Invasive alien species - bycatch	3
		Disturbance - pollution	3
Large petrels and shearwaters	13 (34%)	Invasive alien species - bycatch	8
		Invasive alien species - overfishing	3
Sea ducks and allies	10 (33%)	Hunting/trapping - pollution	7
		Hunting/trapping - bycatch	4
		Invasive alien species - bycatch	3
Cormorants and pelicans	6 (18%)	Problematic native species - overfishing	3

[a] Only included groups with at least five species with at least one terrestrial and one marine threat.

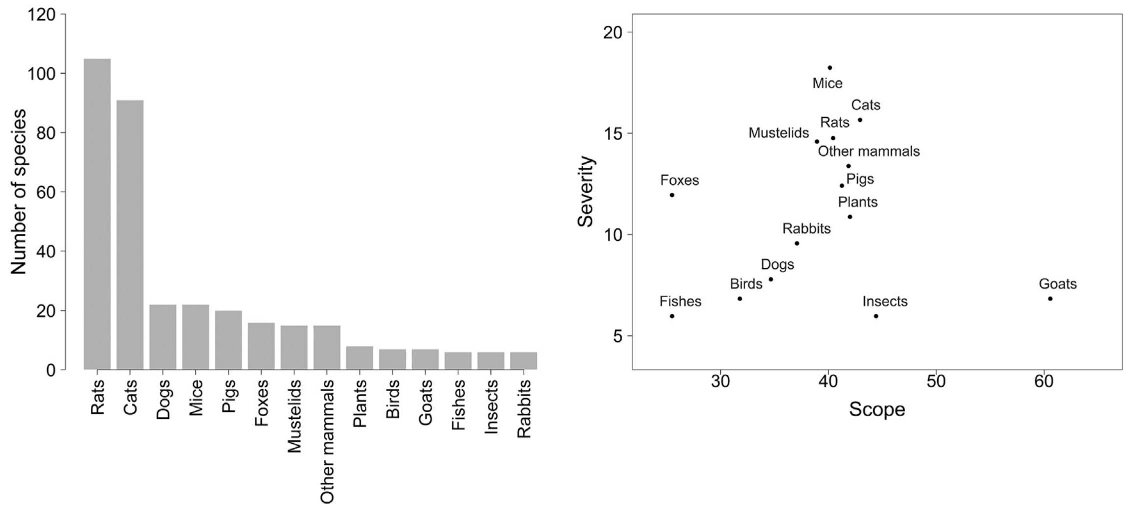

Fig. 5. Left panel: number of seabird species affected by different invasive alien species. Right panel: mean scope and severity of different invasive alien species. Only invasive alien species affecting > 5 seabird species are represented.

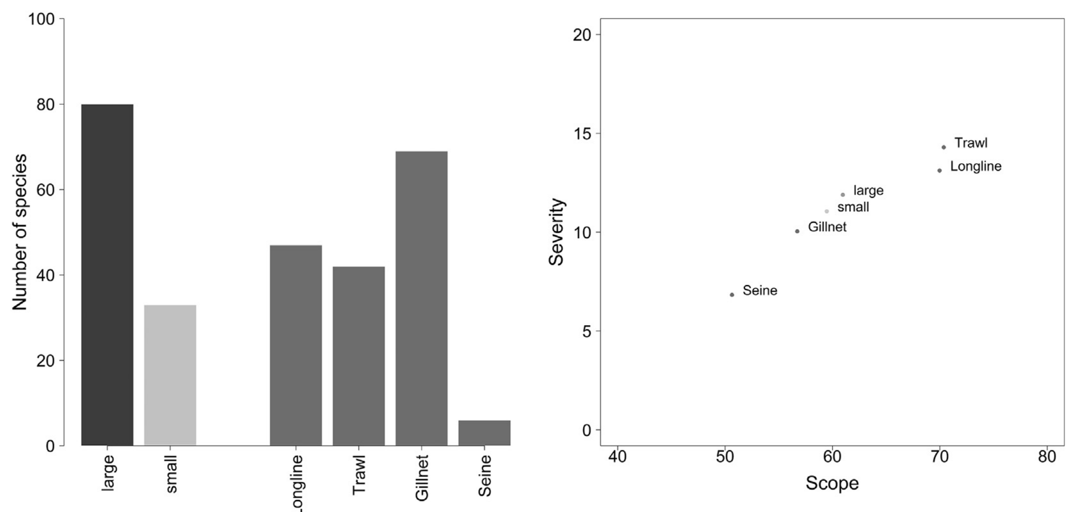

Fig. 6. Left panel: Number of seabird species affected by fisheries (large vs small and different gear types). Right panel: mean scope and severity of large- and small-scale fisheries and of different fishing gear types.

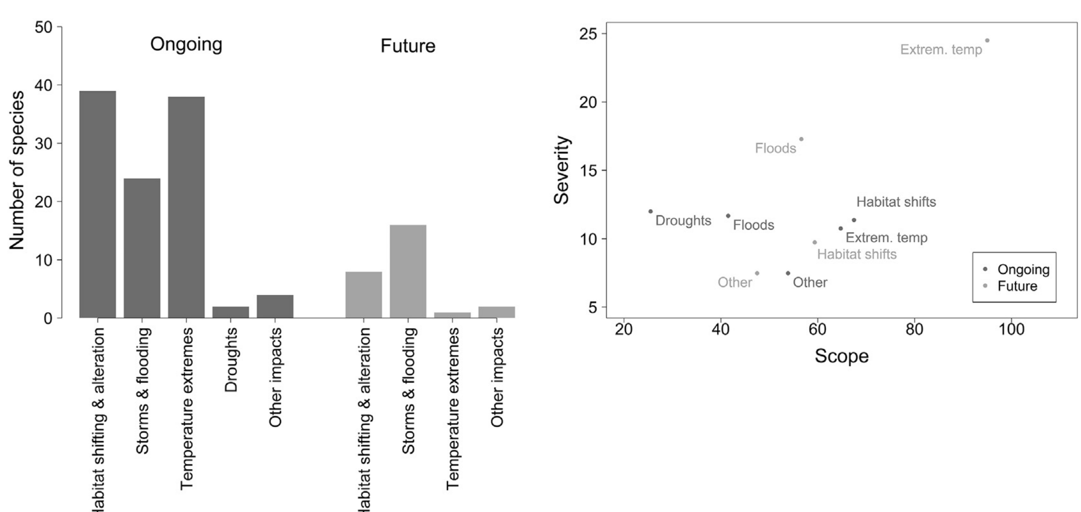

Fig. 7. Left panel: Number of seabird species affected by different "level-2 threats" coded for the threat "climate change/severe weather" (see Table A2.2, Appendix 2). Right panel: mean scope and severity of level 2 threats classified under climate change/severe weather.

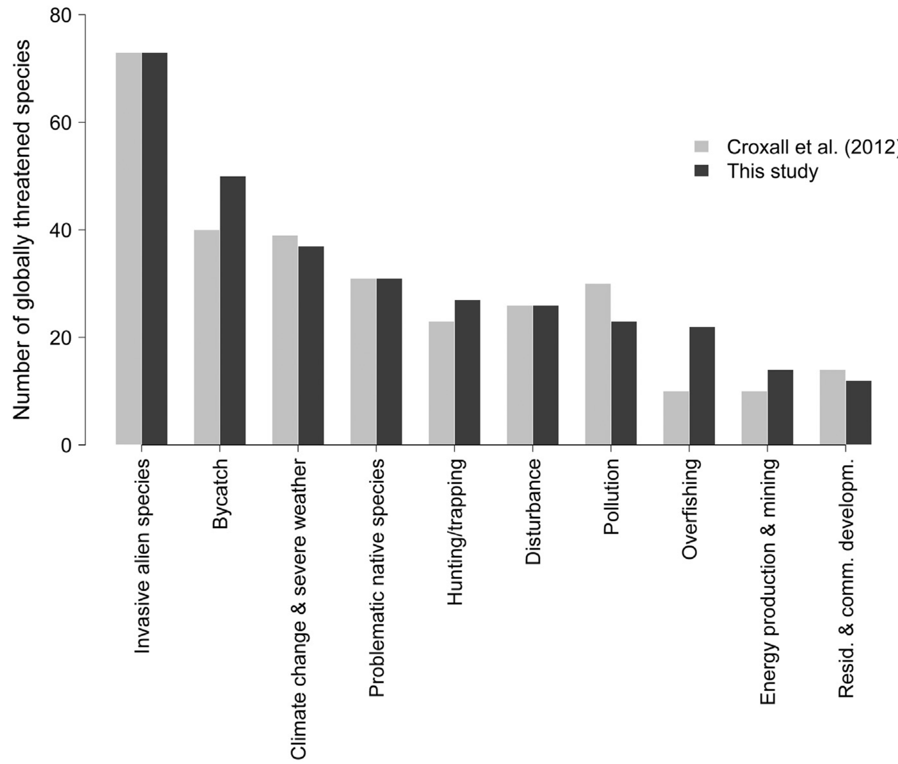

Fig. 8. Comparison between the number of globally threatened seabird species affected by each threat as reported by Croxall et al. (2012) and found in this study. Only threats mentioned in both studies are shown.

of its impact on seabirds when compared with the situation at the end of the last century (Camphuysen, 1998; Clark, 1984).

The top threats currently affecting globally threatened species largely coincide with those affecting NT and LC species with declining trends (Table 2 and Figs. A2 and A3, Appendix 3), which represent one third of all species, and half the total number of individual seabirds. Therefore, tackling the current major problems faced by globally threatened species will also reduce the exposure of hundreds of millions of other (currently non-threatened) seabirds to these threats (Fig. 2).

4.1. Major threats on land

Our study highlighted that invasive alien species, particularly rats and cats, are the major threat to seabird species globally. Therefore, eradication or control of rodents and cats is the major priority in terms of conservation of seabirds at their colonies (Phillips et al., 2016; Spatz et al., 2017; Holmes et al., 2019; Rodríguez et al., 2019) along with enhanced biosecurity measures to prevent re-invasion or new introductions (particularly for sites in proximity to human habitation) and, if necessary and where feasible, post-eradication restoration to provide habitat suitable for recruiting additional seabirds to now-safe sites (Borrelle et al., 2018). The frequent co-occurrence of rats and cats poses an additional challenge in requiring simultaneous eradication (Zavaleta et al., 2001; Rayner et al., 2007).

Hunting/trapping at colonies is the second major threat on land in terms of number of species affected, and the top threat to coastal globally threatened species. This is a well-known issue (Chen et al., 2009; Gaston and Robertson, 2010; Merkel et al., 2014, 2016; Phillips et al., 2016), and needs to be addressed in close collaboration with local communities and authorities. Hunting/trapping can also occur at sea (Bugoni et al., 2008; Alfaro-Shigueto et al., 2016; Frederiksen et al., 2016), although impacts are poorly known (Phillips et al., 2016). Disturbance is also a relevant threat in terms of number of species affected globally, and coastal globally threatened species are particularly affected (Fig. 3). Disturbance of seabirds at their colonies can lead to reduced breeding success (Giese, 1996; Bolduc and Guillemette, 2003; Watson et al., 2014) or even to permanent abandonment of the site (Carney and Sydeman, 1999). The increase of ecotourism activities can pose an additional challenge (Palacios et al., 2018), which is nonetheless solvable by implementing the necessary regulations to control the access to important seabird colonies (Ellenberg et al., 2006).

Other relevant threats on land are light pollution (affecting mostly gadfly petrels, large petrels/shearwaters and storm-petrels; Rodríguez et al., 2017, 2019), problematic native species (especially for cormorants/pelicans, storm-petrels and penguins) and diseases (affecting mostly albatrosses and penguins). These threats also have some known and implementable solutions, such as avoidance or minimization of light sources (especially during fledging periods in high-risk areas; Gineste et al., 2017; Rodríguez et al., 2017), artificial nests for problematic native species competing for nesting burrows (Bolton et al., 2004), and vaccination against diseases in critical cases (Bourret et al., 2018).

4.2. Major threats at sea

We confirmed that bycatch is still a major threat to albatrosses, large petrels/shearwaters and penguins (Trathan et al., 2015; Phillips et al., 2016), and found that large-scale fisheries are driving declines in more than twice as many species as small-scale fisheries (Fig. 6). Although the average impacts (scope and severity) of large and small-scale fisheries seem to be similar, impacts from small-scale fisheries are generally less well-known (Lewison et al., 2004; Chuenpagdee et al., 2006; Soykan et al., 2008). Longline and trawl fisheries involve the gear types with greatest impact in terms of both average severity and scope (especially for albatrosses and large petrels/shearwaters; Tuck et al., 2001; Barbraud et al., 2009).

Many studies have shown that bycatch in longlining and trawl fisheries can be mitigated effectively with the implementation of operational and technical measures. Depending on the characteristics of the fishery, location, season and associated at-risk seabird species, single measures can be effective, such as discard management or bird-scaring lines on trawl vessels (Bull, 2007; Pierre et al., 2012; Maree et al., 2014; Tamini et al., 2015) and hook-shielding devices in pelagic longline vessels (Sullivan et al., 2018). However, measures used in combination are most effective, such as night setting, bird-scaring lines and weighted branch lines for longline vessels (Brothers et al., 1999; ACAP, 2017a, 2017b, 2017c; Domingo et al., 2017; Paterson et al., 2017).

Many Regional Fisheries Management Organisations (RFMOs), and some national fisheries bodies in areas with high bycatch rates, have adopted regulations that seek to minimize bycatch (Anderson et al., 2011; Gilman, 2011; Phillips et al., 2016). The challenge, however, is ensuring practical implementation of the measures and compliance with the regulations, which requires industry-specific solutions and support to ensure validity of the measures and avoid cross-taxa effects (Gilman et al., 2005; Melvin et al., 2019). Gillnet fisheries are thought to affect more species (Fig. 6), especially diving seabirds such as sea ducks and auks (Žydelis et al., 2009). However, the magnitude of the impact of gillnet fisheries on seabird species is still poorly understood (Žydelis et al., 2013; Bærum et al., 2019). Furthermore, and in contrast with the situation for the fishing gears mentioned above, solutions for gillnet bycatch remain elusive and should be regarded as research priorities (but see Mangel et al., 2018; Melvin et al., 1999).

Overfishing is also a top marine threat. It affects fewer species than other top threats, but with considerably greater impact (Figs. 1, 2, Table 2). Overfishing is the main cause of decline of 24 species (e.g. African Penguin *Spheniscus demersus,* Cape Gannet *Morus capensis* and Cape Cormorant *Phalacrocorax capensis*; Pichegru et al., 2010; Crawford et al., 2015; Grémillet et al., 2016) and is often associated with bycatch (> 60% of the species impacted by overfishing are also affected by bycatch). Tackling the problem of overfishing may involve the creation of Marine Protected Areas (Hyrenbach et al., 2000; Lascelles et al., 2012), including no-take zones (seasonal or permanent) in some critical cases (Daunt et al., 2008; Pichegru et al., 2010). However, it chiefly requires the effective implementation of ecosystem-based management of forage-fisheries within the context of wider, multi-stakeholder Marine Spatial Planning (Ardron et al., 2008). Nevertheless, results from recent analysis suggest that we are still failing to implement such management measures and mitigate the impacts of overfishing, as the global catch of fisheries competing with seabirds synoptically increased during the last four decades (Grémillet et al., 2018). We might be also underestimating the magnitude of this problem, given that it has received considerably less attention than other global issues such as climate change (the effects of which are often difficult to disentangle from overfishing; Grémillet and Boulinier, 2009; Sydeman et al., 2012).

4.3. Scope and scale of management approaches

Many seabird species are impacted by multiple threats (three, on average), which can have cumulative impacts on the populations. Several species (72, including 38 globally threatened species and 20 NT) have at least one marine and one terrestrial threat of medium or higher impact. For example, 27 species are impacted by both invasive alien species and bycatch (particularly albatrosses and large petrels/shearwaters, but also some auks and sea ducks; Table 3). Half of the penguin and auk species face a terrestrial and a marine threat with a medium to very high impact (usually invasive alien species or problematic native species and pollution; Table 3). Gadfly petrels and storm-petrels are two notable exceptions to this pattern, as all major threats are land-based (Fig. 4), although this may also reflect the difficulty in assessing at-sea threats to these highly pelagic and nocturnal species (Ramírez et al., 2016; Ramos et al., 2017), whose foraging areas are only now being revealed (e.g. Ramírez et al., 2013; Ramos et al., 2017; Rayner et al., 2008, 2012).

The co-occurrence of medium or high impact terrestrial and marine threats emphasises the need for "ridge to reef" approaches (Rude et al., 2016; IUCN, 2018), whereby management plans aiming to protect seabird species and their habitats should necessarily include measures to address threats both on land and at sea. The appropriate measures at sea depend on the species and the relevant spatial scales of their foraging ranges: whereas short-ranging species such as cormorants and some penguin species benefit most from site-based forms of protection (e.g. well-managed Marine Protected Areas), wide-ranging species such as albatrosses, petrels and shearwaters will also require measures at the larger scale (even Large Marine Ecosystem; Sherman et al., 2003), particularly in relation to effective fisheries management, notably bycatch regulations (Oppel et al., 2018).

4.4. Climate change

Most of the top threats already mentioned (invasive alien species, bycatch, hunting/trapping, disturbance and overfishing) have known and tested solutions, at least in principle and in part. Climate change/severe weather are different in that there is limited prospect of direct mitigation of most of the main known or potential impacts. These include changes in oceanographic processes (resulting in declining in food availability around colonies), increased frequency of extreme weather events, inundation of colonies due to sea level rise or severe rainfall storms, or increased occurrence and virulence of avian pathogens (reviewed by Grémillet and Boulinier, 2009; Barbraud et al., 2012; Sydeman et al., 2012; Phillips et al., 2016). Translocations (and managed retreat) are a possibility in some cases (Deguchi et al., 2014; Miskelly et al., 2009), but challenging to execute for many species, due to the high costs and logistical difficulties.

Nevertheless, we show that most species (89%) affected by climate change/severe weather are also affected by other threats (3.37 ± 0.2 threats on average ± SE), whose impacts are of the same order of magnitude. The most frequent threats co-occurring with climate change/severe weather are invasive alien species, bycatch, overfishing and hunting/trapping (Fig. A5, Appendix 3). This emphasises the crucial importance of addressing effectively these other major threats in order to compensate for the negative impacts of climate change.

4.5. Emerging threats

The problem of marine plastics, which is global and increasing (Ryan et al., 2009; Kühn et al., 2015), and expected to affect virtually all seabird species in a few decades (Wilcox et al., 2015), is not yet identified as a cause of seabird population declines, with only one report so far of plastics causing a significant impact at this level (Flesh-footed Shearwater *Ardenna carneipes*; Lavers et al., 2014). This threat is predicted to have a higher impact on small, highly pelagic species (such as gadfly petrels, storm-petrels, prions and auklets) (Wilcox et al., 2015; Lavers and Bond, 2016; Roman et al., 2019), whose population sizes, demography and at-sea movements are poorly known in many cases, indicating the difficulty in understanding the real impact of plastics at population levels. However, this problem is recent and so a delay would be expected before population impacts become evident for long-lived species, such as most seabirds.

The occurrence and virulence of avian pathogens is also likely to increase, especially at high latitudes, due to the enhanced spread of ectoparasites as a consequence of a warmer climate and to increasing human presence at seabird colonies (Grémillet and Boulinier, 2009; Uhart et al., 2018).

Offshore wind farming (classified here as "Energy production & mining") is another fast-growing issue with potential high impacts on seabirds (Furness et al., 2013), but still with limited information regarding the consequences for seabirds at the population level (Green et al., 2016). This threat is expected to affect mostly coastal species such as divers, scoters, terns and shags (Garthe and Hüppop, 2004), especially via displacement (Furness et al., 2013; Cook et al., 2018). However, highly mobile species can also be at particular risk, due to the cumulative impact resultant from multiple windfarms located across the species distributional range (Busch and Garthe, 2018).

Finally, we anticipate that in a few decades overfishing may become an even more widespread and serious problem for seabirds, including even the more pelagic species. The number of globally threatened species affected by overfishing has more than doubled since the previous assessment based on data collected up to 2010 (Croxall et al., 2012). Depletion of food resources is already regarded as the major cause of decline of 24 species (Table 2), and pressures on stocks of currently exploited coastal forage-fish species are certain to intensify, to the likely detriment of seabirds (Grémillet et al., 2018). In addition, this problem has the potential to increase with the transition of more fisheries to lower trophic levels (Pauly et al., 1998) especially those targeting mesopelagic species (St. John et al., 2016). Mesopelagic fishes, an important part of the diet of many pelagic seabirds, particularly many small nocturnal petrels (Dias et al., 2015; Waap et al., 2017; Watanuki and Thiebot, 2018), are the most abundant marine vertebrates (Irigoien et al., 2014) and remain largely unexploited commercially due to the currently low profitability of fishing deep-water species, especially on the high-seas (St. John et al., 2016; Webb et al., 2010). This situation may soon change due to investment in new fishing technologies, along with the increasing demand for these resources from the aquaculture industry (St. John et al., 2016), with potentially serious implications for their current natural consumers (including seabirds). Despite the difficulty in understanding the complex interactions between seabirds, prey abundance, oceanographic conditions and fisheries, recent studies have shown the detrimental impacts of prey removal on the demography of some species, and highlight the need for defining management objectives for the marine environment that ensure sufficient biomass of forage fish to support seabird communities (Barbraud et al., 2018).

5. Conclusions

Our analysis shows that invasive alien species, bycatch and climate change are the top three threats affecting seabirds globally. Together these threats affect two-thirds of seabird species and hundreds of millions of individuals. Other top threats include overfishing, which affects comparatively few species but with higher impacts, and hunting/trapping and disturbance that affect many species, but with lower impacts. The relative importance of these top threats was largely consistent across different taxonomic groups of seabirds, and when considering only globally threatened species or only NT and declining LC species. These results are also in line with conclusions of some recent threat assessments of well-studied groups of seabirds, such as penguins, albatrosses and petrels (Trathan et al., 2015; Phillips et al., 2016; Rodríguez et al., 2019).

Multiple threats often affect the same species; consequently: a) management approaches tackling simultaneously both marine and terrestrial threats are essential to reverse the declining trend of numerous threatened seabird species; b) the negative effects of climate change can be greatly alleviated by addressing other top threats, for which implementable proven solutions are largely available. However, even for threats with well-known solutions, such as invasive alien species, bycatch and overfishing, there are substantial challenges to overcome. For invasive alien species, many of the priority eradications (Holmes et al., 2019) for islands uninhabited by humans have been completed. Therefore, the focus will increasingly shift to islands with human populations and to mainland areas, both posing substantial problems in relation to mortality of non-target species and control of invasive alien species (as opposed to rapid eradication), which likely require complex, long-term and costly initiatives, even where inherently feasible (Phillips, 2010; Oppel et al., 2011).

Technical solutions to gillnet bycatch have proven hard to develop; in most longline and trawl fisheries compliance with recommended mitigation regulations remains limited (Phillips et al., 2016). Use of remote-recording electronic devices to monitor compliance may be essential to making progress. Seabirds are increasingly impacted by overfishing, especially coastal species. Theoretically, effective ecosystem-based management of marine resources around important seabird colonies can mitigate problems for these particular species, but also requires that effective plans and processes are in place to monitor and enforce compliance. Such potentially effective management systems remain elusive (except at very small scales) anywhere in the world, even within the Economic Exclusive Zones of most developed countries. They are conspicuously absent from the high seas, and radical reform of the RFMOs responsible for such management as does exist is long overdue. Furthermore, the potential detrimental impacts of illegal fishing (e.g. Ortuño Crespo and Dunn, 2017; Petrossian et al., 2018) and of the risk to seabirds of changes in traditional fisheries practices to new models (e.g. reduction fisheries; Smith et al., 2011; balanced harvest; Burgess et al., 2016; Kolding et al., 2016) are practically unknown, and should be a priority area for future research.

Given the continuing deterioration in the conservation status of seabirds, and the increased number and severity of threats confronting them, there is an urgent need to identify and implement practical action to tackle threats to species and sites where feasibility and priority coincide. As seabirds are amongst the best indicators of the status of marine systems, the outlook for the global oceans is not encouraging. However, progress in addressing pollution (Roser, 2018), invasive alien species (Jones et al., 2016) and bycatch (Maree et al., 2014) shows what can be done; effective management of threats in key areas on land and at sea is now the great challenge.

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