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Short Communication

Species' traits and exposure as a future lens for quantifying seabird bycatch vulnerability in global fisheries

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ABSTRACT. Fisheries bycatch, the incidental mortality of non-target species, is a global threat to seabirds and a major driver of their declines worldwide. Identifying the most vulnerable species is core to developing sustainable fisheries management strategies that aim to improve conservation outcomes. To advance this goal, we present a preliminary vulnerability framework for the context of bycatch mortality that integrates dimensions of species' exposure (the extent a species' range overlaps with fishing activities and the magnitude of activities experienced), sensitivity (a species' likelihood of bycatch mortality when it interacts with fisheries), and adaptive capacity (the ability for populations to adapt and recover from bycatch mortalities). This allows us to classify species into five vulnerability classes. The framework combines species' traits and distribution ranges for 341 seabirds, along with a spatially resolved fishing effort dataset. Overall, we find most species have high-vulnerability scores for the sensitivity and adaptive capacity dimensions. By contrast, exposure is more variable across species, and thus the median scores calculated within seabird families is low. We further find 46 species have high exposure to fishing activities, but are not identified as vulnerable to bycatch, whilst 133 species have lower exposure, but are vulnerable to bycatch. The framework has been valuable for revealing patterns between and within the vulnerability dimensions. Further methodological development, additional traits, and greater availability of threat data are required to advance the framework and provide a new lens for quantifying seabird bycatch vulnerability that complements existing efforts, such as the International Union for Conservation of Nature (IUCN) Red List.

Les traits et l'exposition des espèces comme perspective d'avenir pour la quantification de la vulnérabilité des oiseaux marins capturés accidentellement dans les pêcheries mondiales

RÉSUMÉ. Les prises accidentelles dans les pêcheries, c'est-à-dire la mortalité accidentelle d'espèces non ciblées, constituent une menace globale pour les oiseaux de mer et un facteur important de leur déclin dans le monde entier. L'identification des espèces les plus vulnérables est essentielle au développement de stratégies de gestion durable des pêches visant à améliorer les résultats en matière de conservation. Pour atteindre cet objectif, nous présentons un cadre préliminaire de vulnérabilité dans le contexte de la mortalité due aux prises accidentelles, qui intègre les dimensions de l'exposition des espèces (la mesure dans laquelle l'aire de répartition d'une espèce chevauche les activités de pêche et l'ampleur des activités subies), de la sensibilité (la probabilité pour une espèce de subir une prise accidentelle lorsqu'elle interagit avec les pêcheries) et de la capacité d'adaptation (la capacité des populations à s'adapter et à se rétablir des mortalités dues aux prises accidentelles). Cela nous permet de classer les espèces en cinq classes de vulnérabilité. Le cadre combine les caractéristiques des espèces et les aires de distribution de 341 oiseaux marins, ainsi qu'un ensemble de données spatialement résolues sur l'effort de pêche. Dans l'ensemble, nous constatons que la plupart des espèces ont des scores de vulnérabilité élevés pour les dimensions de sensibilité et de capacité d'adaptation. En revanche, l'exposition est plus variable d'une espèce à l'autre, et les scores médians calculés au sein des familles d'oiseaux marins sont donc faibles. Nous constatons également que 46 espèces sont très exposées aux activités de pêche, mais ne sont pas identifiées comme vulnérables aux prises accidentelles, tandis que 133 espèces sont moins exposées, mais sont vulnérables aux prises accidentelles. Le cadre s'est avéré utile pour révéler des modèles entre et au sein des dimensions de la vulnérabilité. D'autres développements méthodologiques, des traits supplémentaires et une plus grande disponibilité des données sur les menaces sont nécessaires pour faire progresser le cadre et fournir une nouvelle perspective pour quantifier la vulnérabilité des oiseaux marins aux prises accidentelles, qui complète les efforts existants, tels que la liste rouge de l'Union Internationale pour la Conservation de la Nature (UICN).

Key Words: *bycatch; longline; purse seine; IUCN red list; seabird; trait; trawl; threatened species; vulnerability; vulnerability framework*

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INTRODUCTION

As of 2018, the global fishing fleet is estimated at 4.56 million fishing vessels of various sizes (FAO 2020). Fisheries bycatch, the incidental mortality of non-target species, is a serious threat to seabirds, driving seabird population declines worldwide (Dias et al. 2019). Therefore, key goals for successful fisheries management and conservation are to identify vulnerable non-target species and develop bycatch mitigation strategies. However, these goals face global challenges because seabirds are wide ranging and encounter fishing activities in various national and international waters at different stages of their life cycle (Komoroske and Lewison 2015). Better understanding of the factor affecting vulnerability of species to bycatch is an essential step toward predicting which species are most at risk and working to mitigate bycatch threats.

Although seabird bycatch is widespread, a global quantification of seabird vulnerability to fisheries bycatch in multiple gear types (e.g., longline, purse seine, and trawl) is presently lacking. This is because bycatch data are often scarce (Anderson et al. 2011, Hedd et al. 2016, Suazo et al. 2017, Zhou et al. 2019) and can be unreliable at quantifying total bycatch because of factors like cryptic mortality (Zhou et al. 2020). Moreover, there is very low observer coverage aboard fishing vessels, and existing data has poor species discrimination and only coarse quantification (Bartle 1991, Weimerskirch et al. 2000, Sullivan et al. 2006, Anderson et al. 2011, Hedd et al. 2016, Suazo et al. 2017). Bycatch mortality of high-risk species may be undetected on board vessels by fishers and observers, and therefore either under- or unreported to databases that collate species' threat data, e.g., the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (http://www.iucnredlist.org/). Coupling traits with fisheries exposure information could offer a complementary lens to existing methods and provide insights into different dimensions of seabird bycatch vulnerability.

Trait-based approaches are important for advancing conservation efforts (Miatta et al. 2021), where traits represent fundamental biological attributes of organisms measured at the individual level (Violle et al. 2007, Gallagher et al. 2020). For example, past ecological risk assessments, such as productivity-susceptibility analyses, have linked traits, range maps, and fisheries data to predict seabird bycatch vulnerability at regional scales (Hobday et al. 2011, Waugh et al. 2012, Small et al. 2013). The recent expansion of freely available seabird trait (Tavares et al. 2019, Richards et al. 2021) and fisheries exposure datasets (e.g., Global Fishing Watch) provide exciting opportunities to progress these existing vulnerability framework methods across gear types at the global scale.

A species' vulnerability to bycatch is determined by both extrinsic (threats) and intrinsic (traits) factors. Specifically, such factors include the interplay between a species' exposure, sensitivity, and capacity to adapt in response to bycatch (Foden et al. 2013, Potter et al. 2017, Butt and Gallagher 2018). First, exposure encompasses the extent a species' range overlaps with fishing activities and the magnitude of activities experienced. For example, wide-ranging pelagic foragers, such as albatrosses, overlap with a variety of fishing gear and fleets throughout their lives (Clay et al. 2019). Second, sensitivity traits represent a species' likelihood of bycatch mortality when it interacts with fisheries. For example, large seabirds have a greater risk of bycatch mortality than smaller seabirds (Appendix 1; Fig A1.1). It is well documented that larger seabirds have greater vulnerability to bycatch in longline fisheries (Zhou et al. 2019, Zhou and Brothers 2021); trawlers particularly impact large, long-winged species because of warp strikes (Lokkeborg 2011, Hedd et al. 2016). Smaller seabirds have been recorded entangled within trawler nets; however, they are generally responsible for a lesser proportion of trawler bycatch mortality (Hedd et al. 2016). It is speculated that fish caught by purse seiners could be too large for small seabird species (Arcos and Oro 2002). Finally, adaptive capacity traits describe the ability for populations to adapt and recover from bycatch mortalities. For example, bycatch will have a greater impact on seabirds with slow reproductive rates, such as albatross and auks, which lay a single egg per season and reach sexual maturity after five to 10 years.

Coupling new datasets of traits and spatially resolved gear-specific fishing activity with seabird global range maps could advance existing methods of ecological risk assessments, thereby providing a new lens for quantifying seabird bycatch vulnerability at a global scale that would complement conservation efforts such as the IUCN Red List. Here we (1) develop a framework for quantifying seabird bycatch vulnerability to multiple gear types; (2) analyze the emerging patterns of seabird bycatch vulnerability based on available data and traits; and (3) discuss future directions and visions for the vulnerability framework.

BUILDING A VULNERABILITY FRAMEWORK

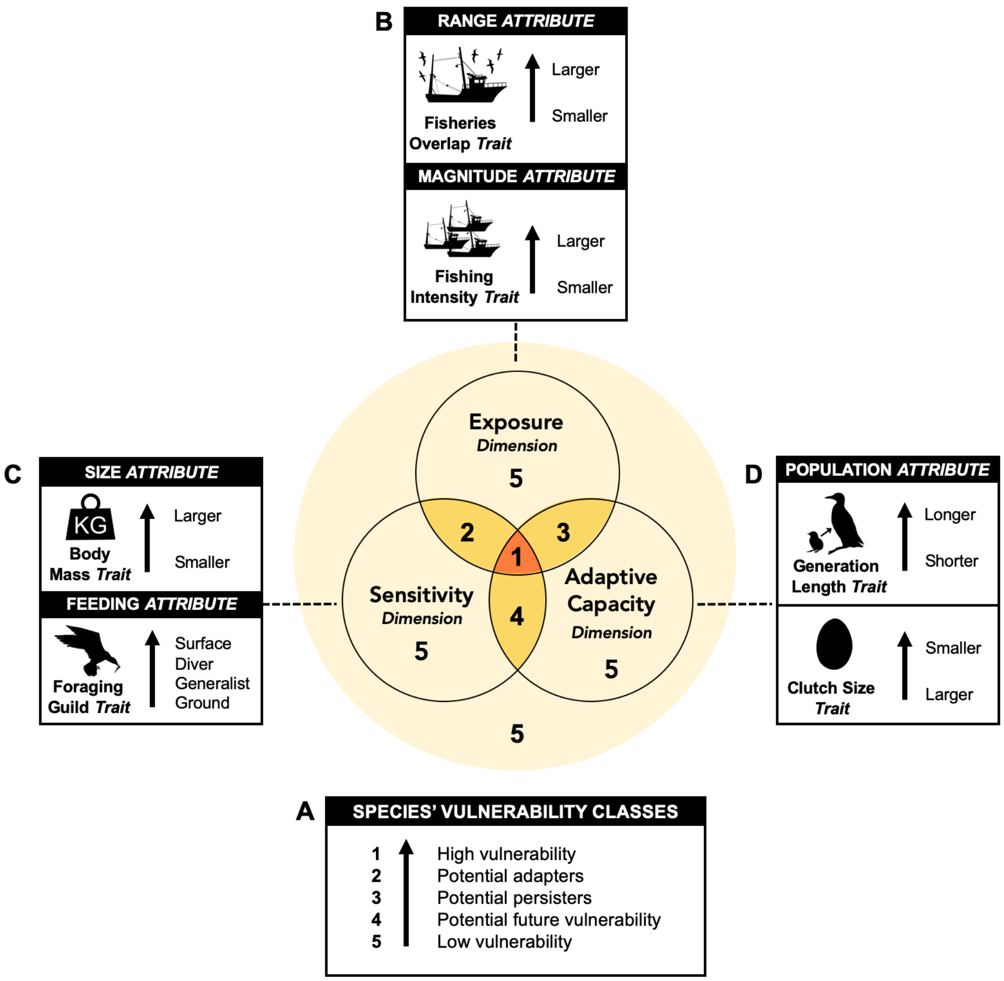
We modified a framework that has previously been applied to a diversity of species from birds and trees to amphibians and corals (Foden et al. 2013, Potter et al. 2017), with the goal of identifying the seabird species most vulnerable to gear-specific bycatch (Fig. 1). Our intention was for the vulnerability framework to be built upon and improved as more trait and threat data become available in the future.

This trait-based framework is built up of three different levels that are nested within one another (Fig. 1). The framework integrates three dimensions of bycatch vulnerability (exposure, sensitivity, and adaptive capacity). Each dimension encompasses a set of vulnerability attributes (size, feeding, range, magnitude, and population) that in turn are represented by species' traits (body mass, foraging guild, fisheries overlap, fishing intensity, generation length, and clutch size). The framework can be used to classify species into five vulnerability classes: high vulnerability, potential adapters, potential persisters, potential future vulnerability, and low vulnerability, based on their dimension scores, which are described in the following sections. Each has implications for conservation prioritization and strategic planning (Foden et al. 2013).

Assessing sensitivity and adaptive capacity to bycatch

We selected body mass and foraging guild (surface foragers, divers, generalists, and ground foragers) to infer the framework's sensitivity dimension (Fig. 1C), and used generation length and clutch size to quantify the adaptive capacity dimension (Fig. 1D). All traits were extracted from a recently compiled dataset of seabird traits (Richards et al. 2021).

Fig. 1. Framework to quantify species' vulnerability to bycatch. The combination of three dimensions: exposure, sensitivity, and adaptive capacity, characterize five distinct species' vulnerability classes (Box A). Six traits associated with five overarching vulnerability attributes (Boxes B–D: range, magnitude, size, feeding, and population) are used to quantify each vulnerability class. Black arrows indicate the direction of increased vulnerability. Modified from Foden et al. 2013 and Potter et al. 2017.



Assessing exposure to bycatch

To estimate the framework's exposure dimension, we quantified: (1) overlap with fisheries activities as the percentage of 1° global grid cells shared between species' ranges and each gear-specific fishing activity, and (2) fishing intensity as the sum of all fishing hours in the overlapping grid cells (Fig. 1B). To achieve this, we extracted distribution polygons for 341 seabirds (BirdLife International 2017), which represent the coarse distributions that species likely occupy, and are presently the best available data for the seabird global ranges. We first created a 1° resolution global presence-absence matrix based on the seabird distribution polygons using the package "letsR" and function lets.presab (Vilela and Villalobos 2015). Second, we downloaded the daily fishing effort data for longlines, purse seines, and trawls, from Global Fishing Watch, which classifies vessel activity based on vessel type and movements (Kroodsma et al. 2018). For each gear type, fishing effort was summed per 1° global grid cell between 2015 and 2018. Finally, to ensure consistency between the species' distribution and gear-specific fishing activity layers, we re-projected all spatial data to a raster format with the same coordinate reference system (WGS84), resolution (1° x 1° global grid cells) and extent (± 180°, ± 90°). To achieve this, we used the package "raster" and function rasterize (Hijmans 2020).

Trait scoring and weighting

Each trait, attribute, and dimension were scored between 0 and 1, with 1 indicating the greatest vulnerability to bycatch (Potter et al. 2017). This was achieved through a stepwise process. First, all continuous traits from the vulnerability dimensions (body mass, clutch size, generation length, overlap with fisheries, and fishing intensity) were broken into categories using the Sturges algorithm, which bins the traits based on their sample size and distribution of values (Sturges 1926). All trait categories were then scored from high to low with ordinal variables based on increased vulnerability to bycatch (Appendix 2–4). To ensure the prioritization analysis predictably weights the criteria (Mace et al. 2007), all scores were scaled between zero and one and weighted by the frequency of trait occurrence (Potter et al. 2017). We weighted the traits based on conservation importance following methods in Potter et al. (2017) because conservation efforts allocated to each species should depend on the proportional number of species within each trait category (Jiménez-Alfaro et al. 2010, Potter et al. 2017).

The following worked example represents the scoring and weighting steps for a trait with four categories: trait category 1 (lowest vulnerability) = 0; trait category 2 = $(n_1 + n_2)/n_{total}$; trait category 3 = $(n_1 + n_2 + n_3)/n_{total}$; and trait category 4 (highest vulnerability) = $(n_1 + n_2 + n_3 + n_4)/n_{total} = 1$, where n is the number of species per trait category and n_{total} is the total number of species. For example, foraging guild contains four categories: ground forager (category 1 = 13 species), generalist forager (category 2 = 63 species), diving forager (category 3 = 121 species), and surface forager (category 4 = 144 species), and n_{total} for this study is 341 species. Ground forager has the lowest conservation priority and is therefore given a score of 0. All other foraging strategies are weighted proportionally based on the number of species within that category and the lower categories (Potter et al. 2017). Therefore, generalist forager's score is (13 + 63) / 341= 0.22, diving forager's score is (13 + 63 + 121)/ 341 = 0.58, and surface foragers, with the greatest conservation priority, have a score of (13 + 63 + 121 + 144)/ 341 =1. These equations are applied to each trait independently.

Species with larger body masses were given a higher trait score (Appendix 2–4) and therefore a greater conservation weight in our vulnerability framework following the worked example. This is because we find that species vulnerable to bycatch in all gear types are significantly larger (t-test, $t = -9.0115$, $df = 300$, $p < 0.001$) than those that are not vulnerable to bycatch (Appendix 1, Fig A1.1). Species with longer generation lengths and smaller clutch sizes were given the highest trait score (Appendix 2–4) and greatest weight because populations with slower reproductive rates will take longer to recover from bycatch mortality.

Vulnerability classes

We categorized species into vulnerability classes (Fig. 1A) based on a dimension score threshold of 55%. This threshold was determined based on a sensitivity test: balancing between excluding all vulnerable species because thresholds were too high, and ensuring minimal species changes between threshold levels across all gear types (Fig. A5.1). If all dimensions (exposure, sensitivity, and adaptive capacity) had a score greater or equal to 55%, species were highly vulnerable to bycatch and classified into the "high vulnerability" class. If the scores of sensitivity and exposure were greater or equal to 55%, but adaptive capacity was less than 55%, species were considered to have high vulnerability with potential adaptive capacity, and were assigned to the "potential adapters" class. If the scores of adaptive capacity and exposure were greater or equal to 55%, but sensitivity was less than 55%, species were considered to have high vulnerability with potential to persist and were assigned to the "potential persisters" class. Species were classified into the "potential future vulnerability" class if the scores of adaptive capacity and sensitivity were greater or equal to 55%, but exposure was less than 55%. If all dimensions had a score less than 55%, or if only one dimension had a score greater or equal to 55%, species had low overall vulnerability and were assigned to the "low vulnerability" class. This approach was repeated for the three gear types (longline, purse seine, and trawl). Thus, all species received vulnerability scores and classes associated with each gear type. All analyses were performed in R version 4.0.2 (R Core Team 2020).

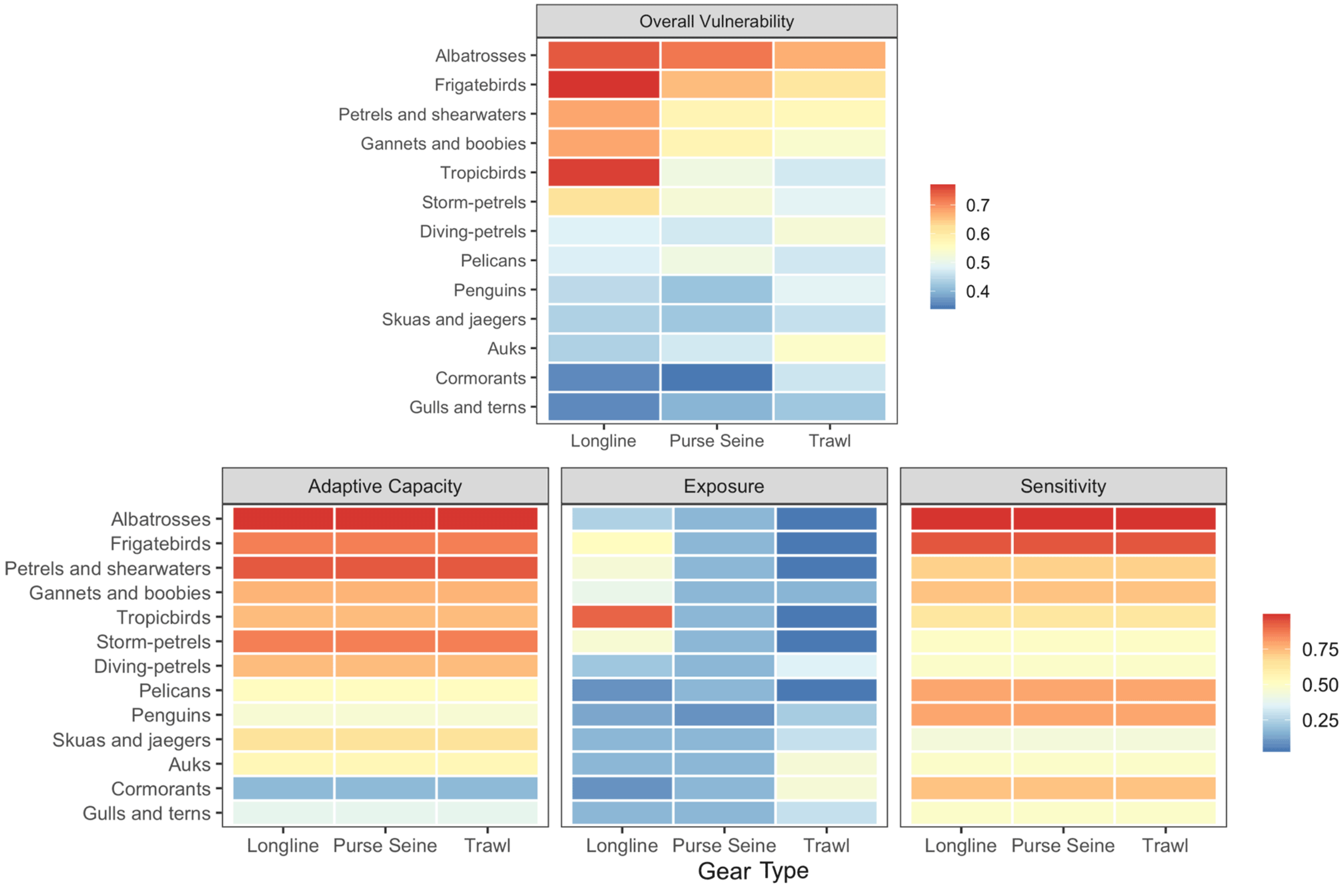
EMERGING PATTERNS OF SPECIES' VULNERABILITY TO BYCATCH

Our preliminary vulnerability framework revealed emerging patterns within the vulnerability dimensions and classes, with species' vulnerability varying across the three gear types and dimensions (Figs. 2 and 3; Appendix 6). Albatrosses had the highest overall vulnerability followed by frigatebirds, petrels, and shearwaters, while gulls, terns, and cormorants had the lowest overall vulnerability (Fig. 2). All seabird families had relatively high sensitivity (median = 0.70) and little capacity to adapt (median = 0.74) in response to bycatch (Fig. 2). By contrast, exposure was more variable and had emerged as an important vulnerability dimension. Although the median exposure across families was low (median = 0.17; Fig. 2), with the exception of tropicbirds, a number of families and individual species had high exposure scores. For example, the Wedge-tailed Shearwater (*Ardenna pacifica*) had a longline exposure score of 0.95, the Northern Fulmar (*Fulmarus glacialis*) had a trawl exposure score of 0.90, and the Black-tailed gull (*Larus crassirostris*) had a purse seine exposure score of 0.97.

Furthermore, we found 46 species had high exposure (score ≥ 75%) to at least one gear type, but were not identified as vulnerable to bycatch by the IUCN threat classification scheme (threats 5.4.3 and 5.4.4 from https://www.iucnredlist.org/resources/threat-classification-scheme). These species were predominantly gulls and terns (n = 16), petrels and shearwaters (n = 13), and storm-petrels (n = 7; Appendix 6). A total of 133 species had lower exposure (score < 75%) to at least one gear type, but were identified as vulnerable to bycatch by the IUCN. These species were predominantly petrels and shearwaters (n = 31), albatrosses (n = 22), auks (n = 19), and gulls and terns (n = 19; Appendix 6).

We further found taxonomic differences between the five vulnerability classes. Specifically, species falling into the high vulnerability class (highest scores across all three dimensions) were predominantly albatrosses, petrels, and shearwaters (Fig. 3; Appendix 6). The most frequent species within the potential adapters class (high sensitivity and exposure scores, but do have adaptive capacity due to low scores) were gulls and cormorants (Fig. 3; Appendix 6). Potential persisters (low sensitivity score, high adaptive capacity, and exposure scores) were typically storm-petrels and shearwaters (Fig. 3; Appendix 6). The potential future vulnerability class (high scores for sensitivity and adaptive capacity, low score for exposure) was commonly composed of albatrosses, petrels, and shearwaters (Fig. 3; Appendix 6). Finally, species classified with low vulnerability (low scores across all dimensions, or a high score for only one dimension) were predominantly gulls and terns (Fig. 3; Appendix 6).

Fig. 2. Median overall vulnerability, adaptive capacity, exposure, and sensitivity scores of all seabird families to longline, purse seine, and trawl gear types.



VULNERABILITY FRAMEWORK LIMITATIONS

The vulnerability framework identified 62% (n = 32) more species that may be vulnerable to bycatch (those falling into the high vulnerability class), but are not currently recognized by the IUCN threat classification scheme as threatened from bycatch. Furthermore, it is important to note that in its present form, the framework mis-classified 36% (n = 70) of the species identified as threatened from bycatch by the IUCN into the low vulnerability class and 44% (n = 64) into the potential future vulnerability class. These differences are likely attributed to limitations in trait selection and data resolution within the vulnerability framework's dimensions. For example, we do not include fine-scale foraging distributions nor a species' propensity to interact with vessels because these data are not available for all seabirds. To increase the framework's value, we encourage its further development based on the criteria outlined in Future Directions for the Framework.

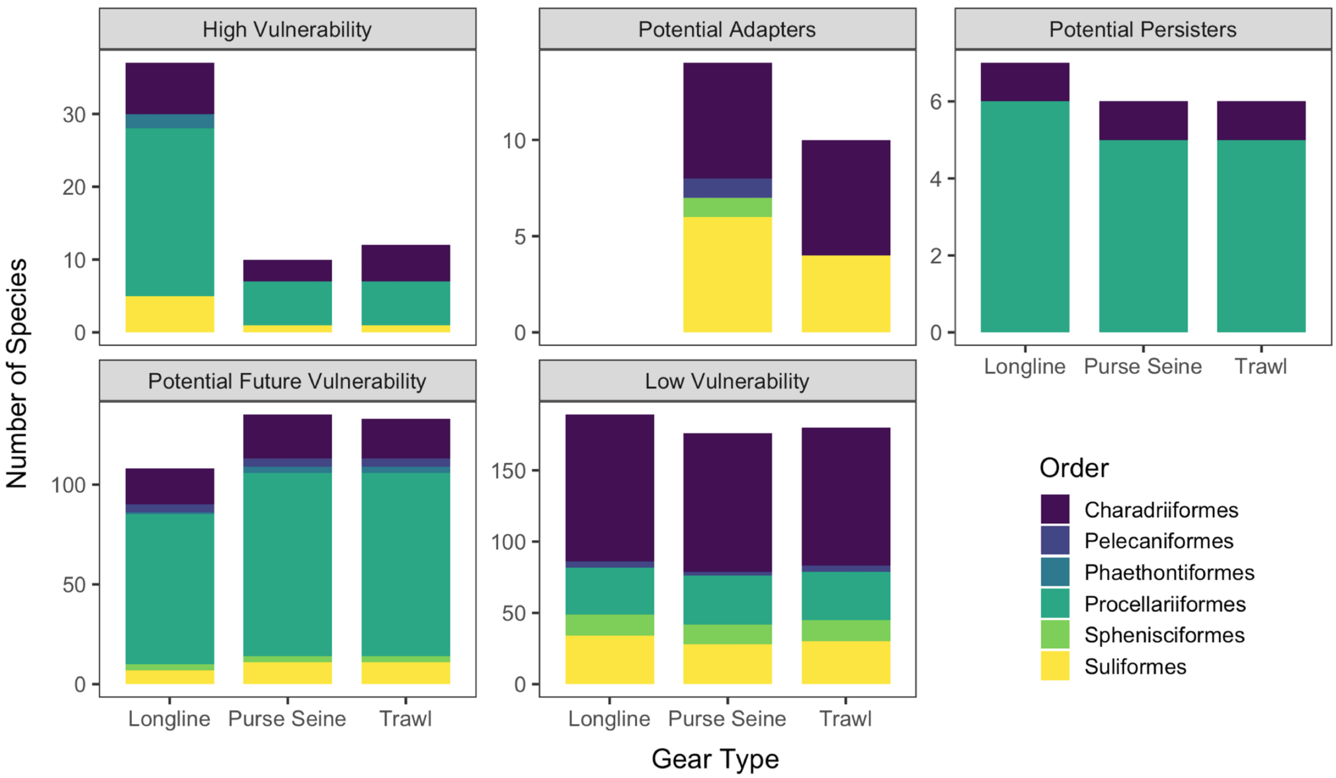
FUTURE DIRECTIONS FOR THE VULNERABILITY FRAMEWORK

Although the framework has been valuable for revealing patterns between and within the vulnerability dimensions, data limitations are presently impeding its full functionality to effectively classify species into their vulnerability classes. However, as additional and finer-scale traits and threat data become available in the future, and because the framework is highly adaptable to spatial and temporal variations in traits and threats, we believe using the additional data could make the framework a valuable tool. To aid in its replication and development in future analyses, we provide the R code used to build the framework.

Trait and dimension improvements

Although an array of traits are available for seabirds, in order to strengthen the vulnerability framework's dimensions, additional efforts are required to compile traits that are not currently available for all seabirds. For example, to improve the sensitivity dimension, future studies may include traits that capture a species' likelihood of interacting with fishing vessels, e.g., boldness, opportunism, competitive ability, and whether they follow ships or not (e.g., Orben et al. 2021). To advance the adaptive capacity dimension, adding additional metrics that relate to breeding and population responses may be important, such as breeding frequency, productivity, and adult survival (Carneiro et al. 2020). Finally, taking advantage of extensive seabird biologging data (e.g., https://www.seabirdtracking.org/) will be imperative to refine the spatiotemporal resolution of the exposure dimension, by shifting the current fishing overlap

Fig. 3. The number of species falling into each vulnerability class for longline, purse seine, and trawl gear types. Charadriiformes encompass gulls, tern, skuas, auks, jaegers; Pelecaniformes are pelicans; Phaethontiformes are tropicbirds; Procellariiformes encompass albatross, petrels, shearwaters; Sphenisciformes are penguins; Suliformes encompass gannets, boobies, cormorants, frigatebirds.



metric to a quantification of fishing interaction rate. Adding information on species abundance distributions and clustering behavior, by identifying areas at sea where birds are attracted to vessels, may further improve the exposure dimension.

Fishing activity data improvements

Fishing activity and seabird distributions vary daily, seasonally, and annually; therefore, we acknowledge the limitation of using four years of aggregated fishing activity data. Future modifications of the vulnerability framework may consider integrating the dynamic changes in fishing activity. Including more gear types could further refine the approach. For example, gillnet fisheries cause an estimated 400,000 seabird mortalities annually (Žydelis et al. 2013); however, we excluded this gear type from our analyses because it presently has poor coverage within the Global Fishing Watch dataset. Finally, distributions of small-scale subsistence, and illegal, unreported, and unregulated (IUU) fishing activities were unavailable, and therefore not included in our vulnerability framework. Incorporating IUU fishing activities in future studies could reveal species with unidentified vulnerability to bycatch.

A FUTURE LENS FOR CONSERVATION

Few management actions have incorporated trait-based analyses into conservation strategies (Miatta et al. 2021). However, we suggest that coupling new datasets of species' traits and fisheries exposure within a vulnerability framework could advance existing ecological risk assessments, such as productivity-susceptibility analyses (Hobday et al. 2011, Waugh et al. 2012, Small et al. 2013), and offer an additional lens to advance ongoing conservation measures and policy, such as the IUCN Red List. For example, there is very low observer coverage aboard fishing vessels, and existing data have poor species discrimination and only coarse quantification (Bartle 1991, Weimerskirch et al. 2000, Sullivan et al. 2006, Anderson et al. 2011, Hedd et al. 2016, Suazo et al. 2017). Thus, bycatch mortality of high-risk species may be undetected on board vessels by fishers and observers, and therefore unreported to fisheries management organizations and not included in threat assessments, such as the IUCN threat classification scheme. The framework could complement vessel-based observations by identifying vulnerable species for which little overall information is known, e.g., revealing the potentially high vulnerability of gadfly petrels (*Pterodroma* sp.) to longline fleets (Appendix 6).

Regional variations and management

The proposed framework could further be extended to explore the regional variations of seabird bycatch vulnerability and to inform regional management actions. For example, the framework can be easily updated based on spatio-temporal variations in fishing activity and additional gear types, and then reapplied at regional scales. The framework also provides the opportunity to evaluate bycatch mitigation successes, such as through comparing how variable approaches in different regions (e.g., exclusive economic zones vs. international waters) and using different mitigation methods (e.g., gear modification and time-area closures) affect species' vulnerability. We therefore highly recommend future studies couple extensive seabird tracking data with colony-specific trait information and regional fisheries patterns to provide a powerful and informative tool for local management, for example, by identifying areas and fisheries where seabird species have high potential bycatch vulnerability, but do not have reliable bycatch data.

CONCLUSIONS

We combined fine-scale fisheries data with seabird traits and coarse-scale seabird distribution data to build a preliminary vulnerability framework that has the potential to identify species at risk from bycatch and help set conservation priorities. Overall, we find most species have high vulnerability scores for the sensitivity and adaptive capacity dimensions. Yet, the framework revealed that species' exposure to fisheries was highly variable, suggesting that vulnerability to bycatch may be dynamic and rapidly change with future developments in fishing. The framework could help identify species that avoid bycatch. For instance, although exposure is a major determinant of vulnerability, some seabirds have high exposure yet are not identified as threatened from bycatch by the IUCN (e.g., tropicbirds). This could be due to a mix of gear types used within the species' range, a species' behavior (e.g., boldness, opportunism), in addition to skewed recording of bycatch by on-board observers. Further work could help understand how these species negate bycatch and how to apply this information to vulnerable species. The framework is highly flexible to trait changes within each vulnerability dimension, we therefore recommend that future studies compile the additional traits, such as fishing interaction rate and boldness, with fine-scale foraging distributions before the framework can be used as a tool to classify species into the five vulnerability classes. Coupling species' traits with fisheries exposure data within a vulnerability framework could be used as an additional lens to aid ongoing conservation measures and policy, such as supporting the efforts of the IUCN Red List and threat identification by suggesting which species need to be especially well investigated and protected.

Responses to this article can be read online at:
https://www.ace-eco.org/issues/responses.php/2033

Author Contributions:

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DATA SHARING AND ACCESSIBILITY

Seabird traits were extracted from (Richards et al. 2021), specifically https://doi.org/10.5061/dryad.x69p8czhd. Species distribution polygons are available upon request from http://datazone.birdlife.org/species/requestdis. Fishing effort data for 2015 and 2016 are available for download, and data for 2017 and 2018 are available upon request from https://globalfishingwatch.org/. R code to build the vulnerability framework is available on GitHub at https://github.com/CerrenRichards/Vulnerability-Framework.

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Appendix 1 – Seabird body size and vulnerability to bycatch

We extracted the information from the IUCN threat classification scheme on whether a species is classified as vulnerable to bycatch or not using the R function rl_threats and package "rredlist" (Chamberlain 2018). Next, using the body mass traits from Richards et al. (2021), we tested whether there was a difference in body size between seabird species that are and aren't threatened from bycatch using a t-test (function t.test in base R).

While the data do not specify which gear type a species is vulnerable to, overall, we find that species vulnerable to bycatch in all gear types are significantly larger (t-test, $t = -9.0115$, $df = 300$, $p < 0.001$) than those that are not vulnerable to bycatch. We therefore give a higher trait score and greater conservation weight to species with larger body masses in our vulnerability framework. For the full description of our scoring and weighting approach, see the Trait Scoring and Weighting section in the main manuscript. However, it is important to note that we consider whether a species is vulnerable to bycatch or not, which is a composite measure of risk. Therefore, this measure not only includes sensitivity, but also other factors. This result only suggests that larger birds are more sensitive.

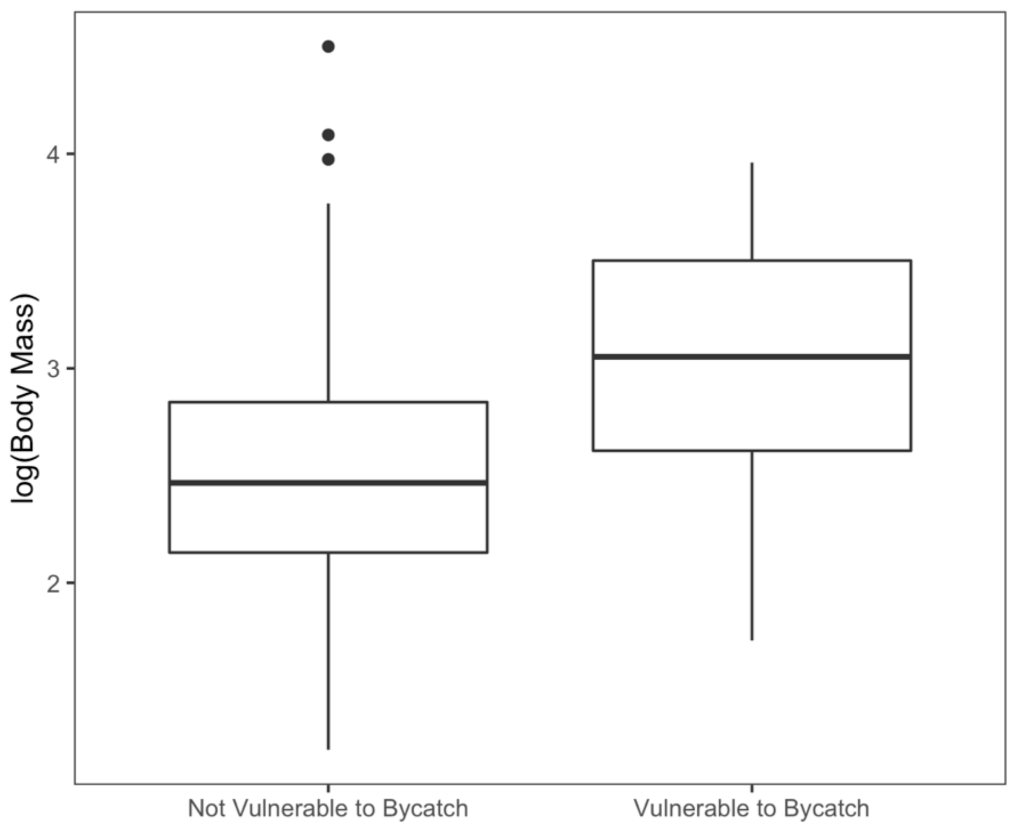

Figure A1.1 The difference in body mass between seabird species identified as vulnerable to bycatch in all gear types and those that are not by the International Union for Conservation of Nature (IUCN) threat classification scheme. Body mass is $\log_{10}$ transformed. The three outliers are Emperor Penguin (*Aptenodytes forsteri*), King Penguin (*Aptenodytes patagonicus*), and Great White Pelican (*Pelecanus onocrotalus*).

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Appendix 2. Purse seine scoring used within the R code (https://github.com/CerrenRichards/Vulnerability-Framework) to build the vulnerability framework

Please click here to download file 'appendix2.csv'.

Appendix 3. Trawl scoring used within the R code (https://github.com/CerrenRichards/Vulnerability-Framework) to build the vulnerability framework

Please click here to download file 'appendix3.csv'.

Appendix 4. Longline scoring used within the R code (https://github.com/CerrenRichards/Vulnerability-Framework) to build the vulnerability framework

Please click here to download file 'appendix4.csv'.

Appendix 5 – Sensitivity test for the change in number of species per percentage threshold

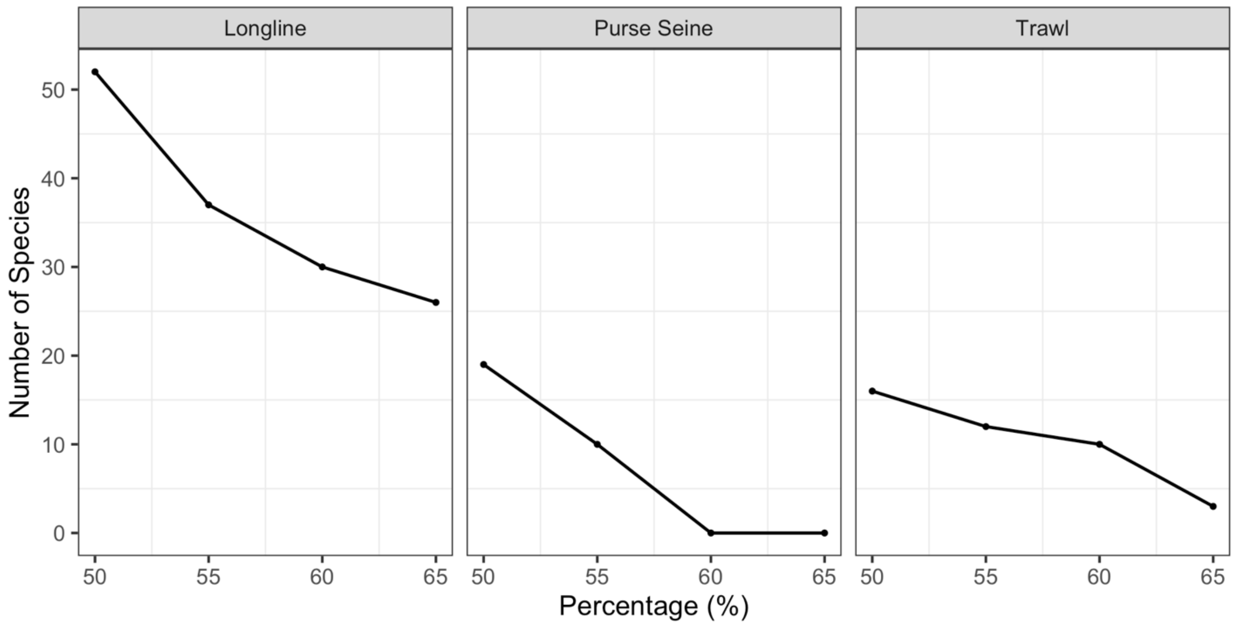

Figure A5.1 Sensitivity test for the change in number of species per percentage threshold for longline, purse seine, and trawl gear types

Appendix 6. Bycatch vulnerability scores for 341 seabird species across three fishing gear types (trawl, longline, and purse seine). The mean of sensitivity, adaptive and exposure scores make up the total vulnerability score. Species are assigned to one of five vulnerability classes based on their sensitivity, adaptive and exposure scores. The IUCN bycatch classification indicates whether a species is (1) or isn't (0) identified by the IUCN threat classification scheme as vulnerable to bycatch.

Please click here to download file 'appendix6.csv'.