



Seabird bycatch risk correlates with body size, and relatively larger skulls, bills, wings and sensory structures

A. M. Heswall¹ · M. R. Friesen² · A. L. Brunton Martin¹ · A. C. Gaskett¹

Received: 3 August 2020 / Accepted: 3 April 2021 / Published online: 23 April 2021
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2021

Abstract

Many animals have sensory biases towards signals or cues that typically provide some fitness benefit. Sensory traps occur when other species or anthropogenic sources produce similar signals or cues but responding is no longer adaptive and can impose significant costs or even death. Bycatch of seabirds by fishing boats has devastating impacts, causing hundreds of thousands of seabird deaths per annum. Here, we explore whether fishing vessels are acting as a sensory trap, inadvertently targeting seabirds with certain life-history traits or larger skeletal or sensory structures. We surveyed the literature to compare seabird order, diet, wingspan, body size, and nesting preference (surface or burrow) of 70 seabirds with varying numbers of reported bycatch in one of the world's most important regions for seabird breeding, in northern Aotearoa New Zealand. We also examined the skeletal and sensory measurements of six seabirds that co-occur spatially in this region, but have different numbers of reported bycatch and indices of bycatch risk. The literature survey revealed that the Charadriiformes and the Sphenisciformes were the most vulnerable groups ($p=0.01$), especially to surface longline fisheries. There were no correlations with diet and foraging behaviour, but surface nesting seabirds and those with larger bodies and wingspans were at a greater risk of becoming bycatch. Skeletal measurements show that species with higher bycatch also have relatively larger skulls, bills and wings, eye sockets and nostrils (relative to body size) ($p<0.05$). This suggests that having a larger overall body size and longer protruding body parts is a primary risk factor, but that species with relatively more sensitive sensory systems likely have even more acute bycatch risk. Considering fishing vessels as sensory traps provides a context to explore the multiple interconnecting factors of sensory sensitivity, sensory bias, behaviour and morphology.

Introduction

Animals use signals and cues to mediate diverse essential behaviours such as foraging, avoiding predation, and detecting mates (Plenderleith et al. 2005; Vincent et al. 2005; Dove 2015). When responding to specific stimuli provides a consistent fitness benefit, sensory biases can evolve whereby animals are preferentially attracted to specific visual or olfactory cues (Basolo 1990; Ryan and Cummings 2013),

associated with behaviours such as foraging (Lequette et al. 1989; Fuller et al. 2010). Sensory traps occur when these cues are produced by other species or anthropogenic sources, but when the animal responds, it is no longer adaptive, imposing significant costs or even death (Christy 1995). For example, birds that use the moon or starlight to navigate can be disoriented by bright lights on buildings or boats (Rodríguez et al. 2015, 2017). Other marine anthropogenic sensory traps are triggered by fish farms, wind farms, and plastic debris, and negatively impact a range of animals including turtles (Schuyler et al. 2014), dolphins (López and Shirai 2007) fish, and whales (Thomsen et al. 2006) and have implications for the survival of individuals, and populations (e.g. Oehlmann et al. 2009).

The negative effects of sensory traps on at-risk wildlife can be mitigated by understanding and implementing measures that use a species' own sensory perception. For example, the sea lamprey, *Petromyzon marinus*, associates specific chemosensory cues with migration or mating (Li et al. 2002). These chemosensory cues can be used as part

Responsible Editor: by V. Paiva.

Reviewers: N. Oliveira and undisclosed experts.

✉ A. M. Heswall
ahes107@aucklanduni.ac.nz

¹ School of Biological Sciences, The University of Auckland, Auckland, New Zealand

² Department of Biology, Saint Martin's University, Lacey, WA, USA

of managing and diverting sea lampreys away from or to certain areas (Johnson et al. 2005). Changing lighting from red to blue on gas rigs has reduced harmful interactions such as migrating birds colliding with structures (Poot et al. 2008). Laser visual deterrents have also proved successful to reduce the mortality of birds at airports (Blackwell and Fernandez-Juricic 2013). Acoustic pingers can reduce the bycatch of dolphins in fishing nets as the harsh auditory cues cause them to swim away from the nets (Bordino et al. 2002). Effective use of sensory manipulations for mitigation requires an understanding of species' sensory physiology and ecology, and how these interact with sensory aspects of the threats (Madliger 2012).

Seabirds are particularly at-risk from human disturbances and have sophisticated sensory systems, making them a highly useful case study to explore sensory traps (Friesen et al. 2017). Approximately half of the ~359 monitored global seabird species have a declining population, and the (IUCN 2019) reports that 11% are near threatened and 31% are globally threatened (Dias et al. 2019). Seabirds may be particularly vulnerable to sensory traps because they share specialized sensory capabilities adapted to living in extreme environments (Catry et al. 2011). Strong selection for sensory modalities may result from seabirds' shared life-history traits, such as living in colonies, where they must identify their mates, burrows, nests or chicks, and foraging at sea, where they must detect prey in the vast expanse of the ocean (Jouventin et al. 1999; Bonadonna et al. 2003; Nevitt 2008; Friesen et al. 2017; Haverkamp et al. 2018). Despite their shared traits, there are still species-level differences in seabird diets and behaviour, with corresponding differences in their sensory modes and capacities (Hayes and Brooke 1990; Mitkus et al. 2016). For example, seabirds that live in denser colonies or forage at night tend to have louder vocal calls than diurnal species (Nelson and Baird 2001; Minguez 1996). Seabirds' reliance on sensory information may make them vulnerable to sensory traps, and seabirds with different sensory traits are likely to be differentially affected.

As for many marine animals, a major risk for seabirds is bycatch, when non-target species are caught unintentionally in the fishing gear of longlines, set-nets and trawls (Davies et al. 2009; Croxall et al. 2012; Reeves et al. 2013; Clarke et al. 2014). Internationally, ~400,000 seabirds are caught annually in set-net fisheries alone (Lewison et al. 2014). Other types of fisheries that report seabirds as bycatch include bottom longline fisheries, trawl fisheries, set-net fisheries, and surface longline fisheries (Abraham and Richard 2017). This has major impacts on population size and the long-term survival of seabird species (Lewison 2004; Dias et al. 2019). The bycatch risk to seabirds is more likely to be heightened in their breeding and foraging zones since both seabirds and fishing vessels target marine zones with abundant fish, e.g. continental shelves inhabited by pelagic

fish, who themselves are attracted to locations of high productivity of lower trophic levels (Piatt et al. 2006).

As well as geographic spatial overlap, bycatch also involves overlap within the water column. Both seabirds and fishing vessels target particular water depths depending on their foraging or fishing methods and target prey. Trawl fisheries use nets fitted with chains and wings to herd fish (Baelde 2001), e.g. with a mesh size of 140 mm and a total sweep length of 144 m and spread of less than 150 m (Huse et al. 2002). Seabirds attempting to scavenge offal discharged from the trawlers can become caught (Wagner and Boersma 2011). Trawlers inadvertently capture diverse seabirds including the black petrel, *Procellaria parkinsoni*, and the Northern giant petrel, *Macronectes halli*, (Abraham and Richard 2017). Longline fisheries release baited hooks that either remain on the surface or can sink up to 300 m (Ward and Myers 2005) and can deploy either 50–100 hooks, 100–300 hooks (Burns 2019), more than 1000 hooks, or even up to 6000–8000 hooks (Huse et al. 2002). These are likely to be most risky for seabirds that use surface foraging and surface dipping or skipping, which is common among many shearwater and petrel species (Miskelly 2013). Fluttering shearwaters, *Puffinus gavia*, and storm petrels (Shealer 2002) are often reported as bycatch for bottom and surface longline fisheries (Abraham and Richard 2017). Set-nets can vary in sizes depending on the target fish species (Žydelis et al. 2013), e.g. a set-net fishery operating off the California and Oregon coast having a mesh size of approximately 43–56 cm, and a net length of approximately 1830 m (Barlow and Cameron 2003), while other mesh sizes vary from 15 to 250 mm (Žydelis et al. 2013). The birds most affected by set-nets are guillemots, penguins and sea ducks (Žydelis et al. 2013) as well as seabirds which are likely to be plunge divers such as gannets and boobies (Forsell 1999; Shealer 2002) and pursuit divers including auks and shearwaters (Tull et al. 1972). In general, many seabirds feed via kleptoparasitism and scavenging (Miskelly 2013) and may become accidentally entangled in the fishing gear of any type when they attempt to feed on bait. Fishing vessels, gear, burley, bait and offal could generate strong visual, olfactory, and auditory stimuli for seabirds and other marine predators.

A seabird species' risk of bycatch is undoubtedly enhanced when the movements of seabirds and boats overlap, both across the ocean and within the water column, and the relative seabird population size (Dias et al. 2019). However, even when seabird species co-occur spatially with each other, and when their different population abundances are taken into account, some seabird species are still more likely to be reported as bycatch (see Supplementary Tables 1 and 2). It is unclear why some seabird species are more vulnerable to bycatch than others. Body shape and size influence shark bycatch (Gallagher et al. 2014), and the same may occur for seabirds, but

more research is required. Larger body size, or longer bills or wings, could possibly increase the risk of becoming entangled in fishing gear. For example, Salvin's and white-capped albatross (*Thalassarche salvini*, *Thalassarche steadi*) have large body sizes (up to 950 cm), and they have high numbers of reported bycatch (476 and 394 reported in 2013, c.f. Supplementary Table 1, Miskelly 2013; Richard and Abraham 2013). Comparative, multi-species analyses of seabird morphology and rates of bycatch could reveal correlations between body size, wing, leg or beak length and the risk of becoming entangled.

Another untested factor that could explain species-level differences in bycatch risk could be species-specific variations in seabird sensory systems, leading to different rates of attraction to fishing operations. Fishing vessels may act as an irresistible sensory trap, offering compelling multimodal sensory attractants (Friesen et al. 2017). Some seabird species such as the short-tailed albatross, *Phoebastria albatrus*, black-browed albatross, *Thalassarche melanophris*, and Cape and Northern gannets, *Morus capensis*, *M. bassanus*, are strongly attracted to the visual appearance of fishing vessels (Suryan et al. 2008; Votier et al. 2013; Tremblay et al. 2014; Collet et al. 2017). At close-range, species such as wandering albatross, *Diomedea exulans*, which have extremely sensitive vision (Hayes and Brooke 1990), may even be able to detect baited hooks or chum. In general, species with larger eyes tend to have better vision (Kiltie 2000). As well as vision, seabirds can use olfaction to detect odours associated with prey (or other resources such as mates or chicks) at both long-distance and close range (Nevitt 1999). Fishing vessels, bait and offal are likely to generate strong olfactory attractants for seabirds. Seabird species with more acute vision or olfaction may be at greater risk of becoming bycatch than other species with less sensitive sensory systems.

Here, we aim to explore whether ecological and sensory traits correlate with seabirds' reported and calculated risks of bycatch. We collated data from the literature about body size, diet, foraging and nesting behaviour of 70 Aotearoa/New Zealand seabird species regularly reported as bycatch. Then, we measured the skeletal morphology along with eye and nostril socket volumes of museum specimens from six co-occurring seabird species with different numbers of reported bycatch and risks.

We hypothesise that seabird species with higher bycatch rates or risks will share similar traits. If bycatch relates primarily to overlap in target species and fishing zones in the water column, we predict that seabird diet and foraging behaviour could be correlated with bycatch risk. If bycatch is due to physical entanglement with the fishing gear, we predict that larger birds with relatively longer bills and wings will be caught more often. If fishing boats act as sensory traps, we predict that birds with a relatively larger

eye and nostril sockets will most likely be at the greatest risk of bycatch.

Methods

Study area

We focused our research on the Hauraki Gulf, Aotearoa New Zealand. New Zealand is one of the world's most important sites for seabirds, with more resident seabird species than any other region (88 species). Northern New Zealand is the breeding site for ~25% of the world's seabird species. The Hauraki Gulf is an area of particular seabird richness, supporting ~27 species of seabirds (Gaskin and Rayner 2013; Miskelly 2013). The Hauraki Gulf also has high cargo, tourism and fishing demands. It is used regularly by 7658 trawls, and 800 Danish seine net operations and more than 150 longliners (Hauraki Gulf Forum 2020). Unfortunately, this report does not provide information on the abundance of set-net fisheries in the Hauraki Gulf as data on it could not be found. The catch per unit effort has generally decreased, but for some fishing operations there is an increased effort in smaller zones (Hauraki Gulf Forum 2020).

Study species

A list of 70 candidate study species reported as bycatch in New Zealand waters was collated from the New Zealand Aquatic Environment and Biodiversity Report (Richard and Abraham 2013; Online Supplementary Table 1). These 70 species occur in the Hauraki Gulf as well as the wider surrounding area in New Zealand waters. Six study species were chosen for further sensory and morphological analysis. These species forage within the same area, the Hauraki Gulf, New Zealand, but have different numbers of reported bycatch (Richard and Abraham 2013; Abraham and Richard 2017). We focused our study on six seabird species in the Hauraki Gulf with sufficient museum specimens, to get an initial understanding of how sensory, morphology, and behaviour impact bycatch. We chose three species with high bycatch risk (greater than 100 deaths reported in 2013): sooty shearwater (hakoko, *Ardenna grisea*, $n = 539$), flesh-footed shearwater (toanui, *Puffinus carneipes*, $n = 333$) and black petrel (taiko, *Procellaria parkinsoni* $n = 693$), and three with low bycatch risk (less than 50 deaths reported in 2013): fluttering shearwater (pakaha, *Puffinus gavia*, $n = 10$), Buller's shearwater (rako, *Puffinus carneipes*, $n = 5$), and common diving petrel (kuaka, *Pelecanoides urinatrix*, $n = 14$). (n is the reported bycatch number for individual species).

Bycatch data

We used six measures of bycatch: the reported bycatch number (absolute numbers reported as caught), a risk ratio, and a vulnerability value for different types of fishing (trawler, bottom longliner and surface longliner and set-nets). The reported bycatch numbers were extracted from a government report on New Zealand seabird bycatch by commercial fisheries from 2006–2011 within the New Zealand exclusive economic zone (NZ EEZ), (Richard and Abraham 2013). The reported bycatch numbers are the numbers of seabird captures observed and reported per annum, which does not take into account cryptic mortality (seabirds that died but were not taken on board the vessel; Coggins et al. 2007).

The bycatch ‘risk ratio’ is the estimated potential number of annual seabird mortalities from bycatch (from observer reports in 2006–07 and 2010–11 throughout the NZ EEZ), relative to the potential biological removal (PBR), (Richard and Abraham 2013). PBR is the estimated number of seabirds killed without producing a decline in the seabird population below half the carrying capacity.

$$PBR = \frac{1}{2} \rho r \frac{NL}{\max} N \frac{G}{\min} f \quad (1)$$

For Eq. 1 from (Richard and Abraham 2013), ρ is a calibration factor and is dependent on the species (either 0.17 or 0.61); $r \frac{NL}{\max}$ is the estimated maximum growth rate for each species under optimal conditions and $N \frac{G}{\min}$ is the population size estimate. This risk ratio takes into account the relative abundance of each species, and cryptic mortality, which was calculated according to the bird species and fishing method and assumes the seabirds are from land-based populations (Richard and Abraham 2013).

The final bycatch measure we used was the vulnerability to four fishing methods (trawler, set-net, bottom longline and surface longline) was calculated by the estimated product of a constant, v_0 , multiplied by a species-group vulnerability (when seabirds having smaller populations were aggregated to a single group to enhance the estimation of fatalities of those seabird species) and a fisheries-group (fisheries were assigned to a group based on the target species, the size of the vessel and type of vessel) vulnerability, (Richard and Abraham 2013).

$$C_{gs} \sim \text{Poisson}(\mu_{gs}). \quad (2)$$

For Eq. 2, C_{gs} is the number of captures for each species (s) observed annually in the fishery (g), μ_{gs} is the mean number of captured observed for the species (s) within the fishery (g), (Richard and Abraham 2013). The constant v_0 is the vulnerability of the white-chinned petrel species to capture in the different types of fisheries (trawl, bottom and surface longline) and is a fixed base case.

Seabird traits and skeletal measurements

For the 70 seabird species (Supplementary Table 1) we collated trait data from online resources, literature and databases including seabird order, diet, nesting behaviour (surface or burrow), wingspan and body length (New Zealand Birds Online; Miskelly 2013). The body length was categorized into three different categories: small (between 0–500 cm), medium (between 500–750 cm) and large (> 750 cm). For the six species chosen for further skeletal analyses, we took morphometric measurements of museum skeletal specimens from the Museum of New Zealand Te Papa Tongarewa, the Canterbury Museum, and the Auckland War Memorial Museum Tāmaki Paenga Hira. Measurements comprised: skull length, skull width, skull depth, bill length, bill width, bill depth, humerus length, radius length, ulna length, carpometatarsus length, femur length, tibiotarsus length, tarsometatarsus length, and wing length. We also measured the length, width and depth of the eyeball socket and nostril, to estimate eyeball socket volume and nostril socket volume. All available specimens of each species were used to calculate the mean of each morphological and sensory trait of each of the six species. We also classified species into a high number of reported bycatch (values of 333, 539 and 693) or a low number of reported bycatch (values of 5, 10 and 14), and provide the median value for each morphological trait for each species in these categories.

Morphometric measurements were made with digital callipers rounded to the nearest 0.01 mm. The bill width was measured near the bill’s horn. The bill depth was measured near the bill’s base. To determine the size of each of these relative to body size, we divided by the length of the tarsometatarsus (or leg length), a common proxy for body size (Senar and Pascual 1997) so that we measured the relative (not absolute) size of each feature. Our results provide evidence of some general patterns and correlations between traits and bycatch risk.

We chose the traits of seabird order, diet, wingspan length, body length and nesting behaviour (surface or burrow) to examine if there are life history and morphological traits associated with different bycatch numbers and fishery risk ratios.

Ethical statement

This research involved collating data from the literature and measuring museum specimens so no formal animal ethics approval is required. All museum specimens were accessed via permission from museum curator.

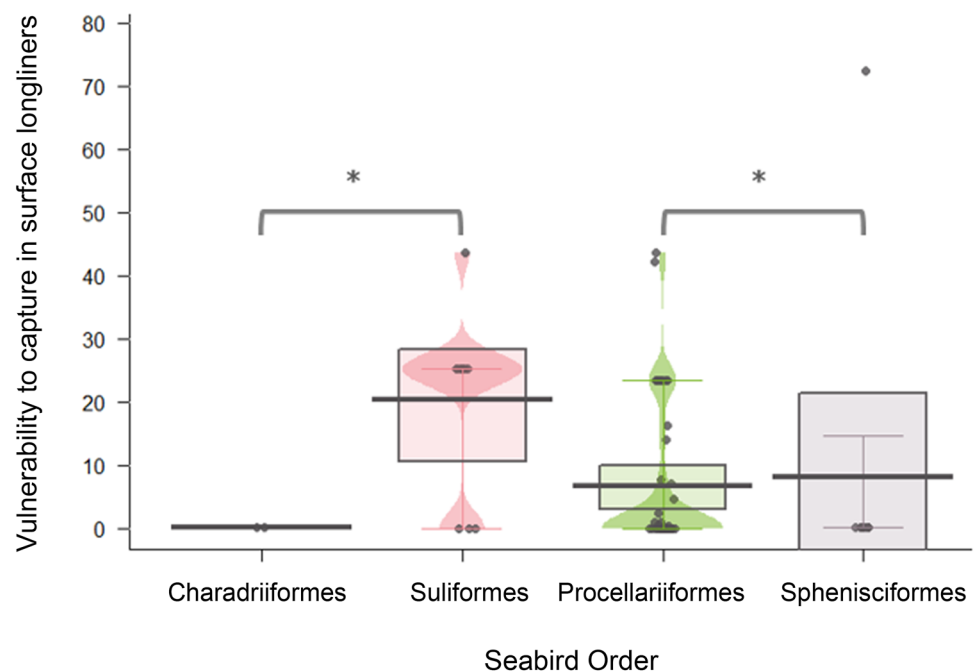
Statistical analysis

For the dataset of 70 seabirds, to test whether seabird order, diet, wingspan length, body length and nesting behaviour correlated with bycatch, risk ratio and vulnerability to trawling, surface longlining, bottom longlining and set-netting, we carried out multivariate multiple regression (MASS in R 3.5.1, backwards selection, RStudio Team 2016). We report Pearson's R^2 as a measure of effect size for these models.

For the sensory and morphometric analysis of the six seabird species (Buller's shearwater, $n = 77$, fluttering shearwater, $n = 99$, common diving petrel, $n = 126$, sooty shearwater, $n = 123$, flesh-footed shearwater, $n = 65$, and black petrel, $n = 64$), we used ordinal multivariate multiple regression (MASS in R 3.5.1) to test for correlations between the morphological traits relative to body size (i.e. tarsometatarsus length) and the different measures of bycatch (reported bycatch, risk ratio, vulnerability to trawling, surface longliners, bottom longliners and set-net fisheries). We report Pseudo R^2 as a measure of effect size for these models (McFadden's log-likelihood).

These measurements relative to tarsometatarsus (body size) and these statistical analyses take into account any allometric co-correlations. We tested for autocorrelation in the traits relative to body size and removed the redundant variables. For both models, we tested assumptions of normality and equality of variance. Data were log-transformed where necessary.

Fig. 1 Survey analyses using multivariate multiple regression of the seabird order and their vulnerability to capture in surface longliners. Pink represents Suliformes. Green represents Procellariiformes. Violet represents Sphenisciformes. Significant differences were indicated with brackets and * symbol. Box indicates 95% confidence interval, dark line indicates the median and whiskers indicates the interquartile range. Raw data are presented here, statistical analyses were carried out with transformed data



Results

Seabird traits

There was no significant correlation between the seabird order and reported bycatch, the bycatch risk ratio, or vulnerability to most of the different fishing methods. However when the Suliformes were compared to Charadriiformes and when Procellariiformes were compared to Sphenisciformes the Charadriiformes and the Sphenisciformes were significantly more vulnerable to surface longline fishing ($p = 0.01$; Fig. 1; Table 1). Diet did not significantly correlate with reported bycatch, risk ratio or vulnerability to different fishing methods (Table 1).

Burrow nesters were more likely to be caught as bycatch than surface nesters ($p < 0.05$; Table. 1; Fig. 2). In addition, some morphological measurements correlated with bycatch. As the wingspan relative to body length increased, so did vulnerability to capture in trawl ($p < 0.05$), bottom longline ($p = 0.03$), and set-net fisheries ($p < 0.05$; Table. 1). Body length positively correlated with reported bycatch, ($p < 0.05$), but negatively correlated with vulnerability to capture in bottom longline, ($p = 0.01$; Table 1).

Skeletal measurements

For the six seabirds for which we took morphological measurements, there are significant correlations between nearly all measured morphological traits (relative to body size) and all measures of bycatch. Bill length and wing length relative

Table 1 Multivariate multiple regression analysis of the survey

	Reported bycatch	Risk ratio	Vulnerability to capture in trawl fisheries	Vulnerability to capture in bottom longline fisheries	Vulnerability to capture in surface longline fisheries	Vulnerability to capture in set-net fisheries
Suliformes: charadriiformes	-0.98	-0.99	-0.99	+0.99	+ <0.05*	+0.57
Procellariiformes: sphenisciformes	+0.76	+0.99	-0.78	+0.98	+0.03*	+0.07
Diet of Krill	+0.18	+0.96	+0.19	+0.51	-0.70	+0.85
Surface nester	-0.03*	-0.56	-0.86	+0.88	-0.25	+0.35
Wing span	+0.26	+0.53	+0.01*	+0.03*	+0.80	+ <0.05*
Body length	+ <0.05*	+0.07	+0.07	+0.02*	+0.12	+0.20
Model R2	0.40	0.57	0.30	0.37	0.45	0.30

Significant values ($p < 0.05$) are in bold and marked with *. Positively associated values are marked with + and negatively associated values are marked with -

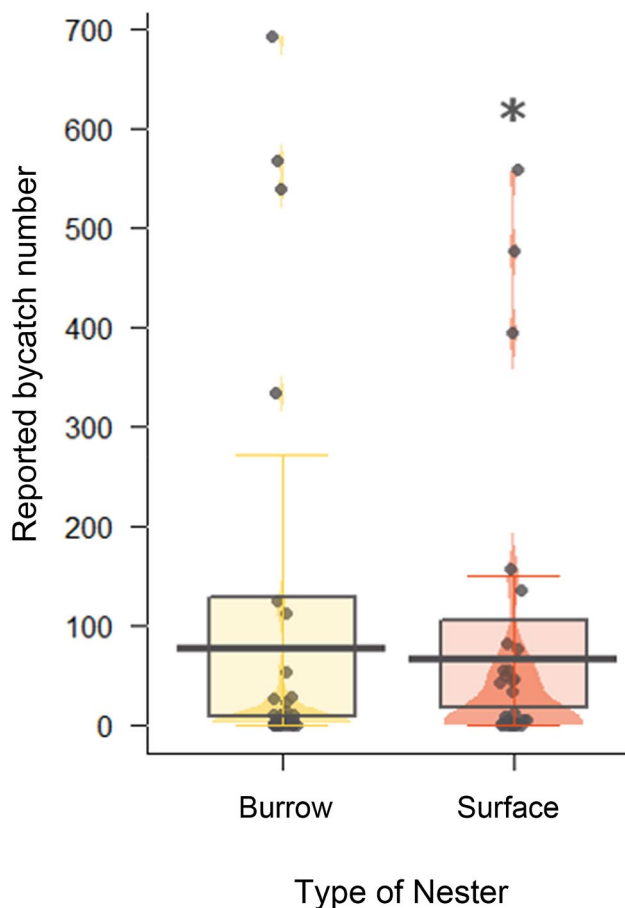


Fig. 2 Survey analyses of the multivariate multiple regression of the type of nester and the number of reported bycatch. Significant difference indicated with * symbol. Yellow represents burrow nesting seabirds. Red represents surface nesting seabirds. Box indicates 95% confidence interval, dark line indicates the median and whiskers indicate the interquartile range. Raw data are presented here, statistical analyses were carried out with transformed data

to body size all had significant correlations with reported bycatch, risk ratio and the vulnerability to the different types of fishing vessels ($p < 0.05$; Table 2). The total number of sensory pits correlated to a higher reported bycatch, risk ratio and vulnerability to capture in trawl and set net fisheries ($p < 0.05$; Table 2). Eye socket volume relative to body size had a significant correlation, increasing with risk ratio and the vulnerability to all bycatch measures ($p < 0.05$; Table 2; Fig. 3), with the exception of the reported bycatch. Nostril socket volume relative to body size correlated with reported bycatch, risk ratio and the vulnerability to different fishing methods ($p < 0.05$; Table 2) except with the surface and bottom longline fisheries. Overall, relative to body size, the chance of bycatch and vulnerability to becoming bycatch increased as skull length, wing length, eye socket volume and nostril socket volume increased (Fig. 3).

Generally, the species caught in greater numbers (black petrel, sooty shearwater and flesh-footed shearwater) have a smaller skull length, larger wing length, eye socket volume and nostril socket volume relative to body size (Fig. 4). Whereas, the species caught less often (Buller's shearwater, fluttering shearwater and common diving petrel) have a larger skull length, and smaller wing length, eye socket volume and nostril socket volume relative to body size (Fig. 4).

Discussion

We show in a broad, multi-species context that some seabird traits and morphologies could correlate with the risk of becoming fisheries bycatch. The most vulnerable seabird species are those that are larger bodied, with relatively larger wings, eyes and nostrils (relative to their body size).

We predicted that seabirds would be most at risk of becoming bycatch when their diet matches the target fish or bait types used by fishing vessels, or their foraging

Table 2 Multivariate multiple regression analysis of the morphological and sensory measurements relative to tarsometatarsus of six seabird species with higher reported bycatch (list species) and lower reported bycatch (list species), in New Zealand waters (Richard and Abraham 2013)

	Reported bycatch	Risk ratio	Vulnerability to capture in:			
			Trawl fisheries	Bottom longline fisheries	Surface longline fisheries	Set-net fisheries
Skull length	-.32	-0.28	- < 0.05*	+ < 0.05*	+ < 0.05*	+0.17
Skull width	< 0.05*	+0.11	+ < 0.05*	- < 0.05*	- < 0.05*	+0.66
Skull depth	-0.13	-0.28	-0.31	- < 0.50*	- < 0.05*	+0.20
Bill length	-0.03*	- < 0.05*	- < 0.05*	- < 0.05*	- < 0.05*	-0.03*
Bill width	-0.02*	- < 0.05*	- < 0.05*	- < 0.05*	- < 0.05*	-0.42
Bill depth	-0.02*	- < 0.05*	- < 0.05*	- < 0.05*	- < 0.05*	+0.22
Wing length	+0.04	+ < 0.05*	+ < 0.05*	+ < 0.05*	+ < 0.05*	+ < 0.05*
Number of sensory pits	+ < 0.05*	+ < 0.05*	+ < 0.05*	-0.41	-0.41	+ < 0.05*
Eye socket volume	-0.48	+ < 0.05*	+ < 0.05*	+ < 0.05*	+ < 0.05*	+ < 0.05*
Nostril socket volume	+ < 0.05*	+ < 0.05*	+ < 0.05*	-0.52	-0.72	+ < 0.05*
Model R2	0.40	0.63	0.55	0.40	0.40	0.74

Significant values ($p < 0.05$) are in bold and marked with *. Positively associated values are marked with + and negatively associated values are marked with -

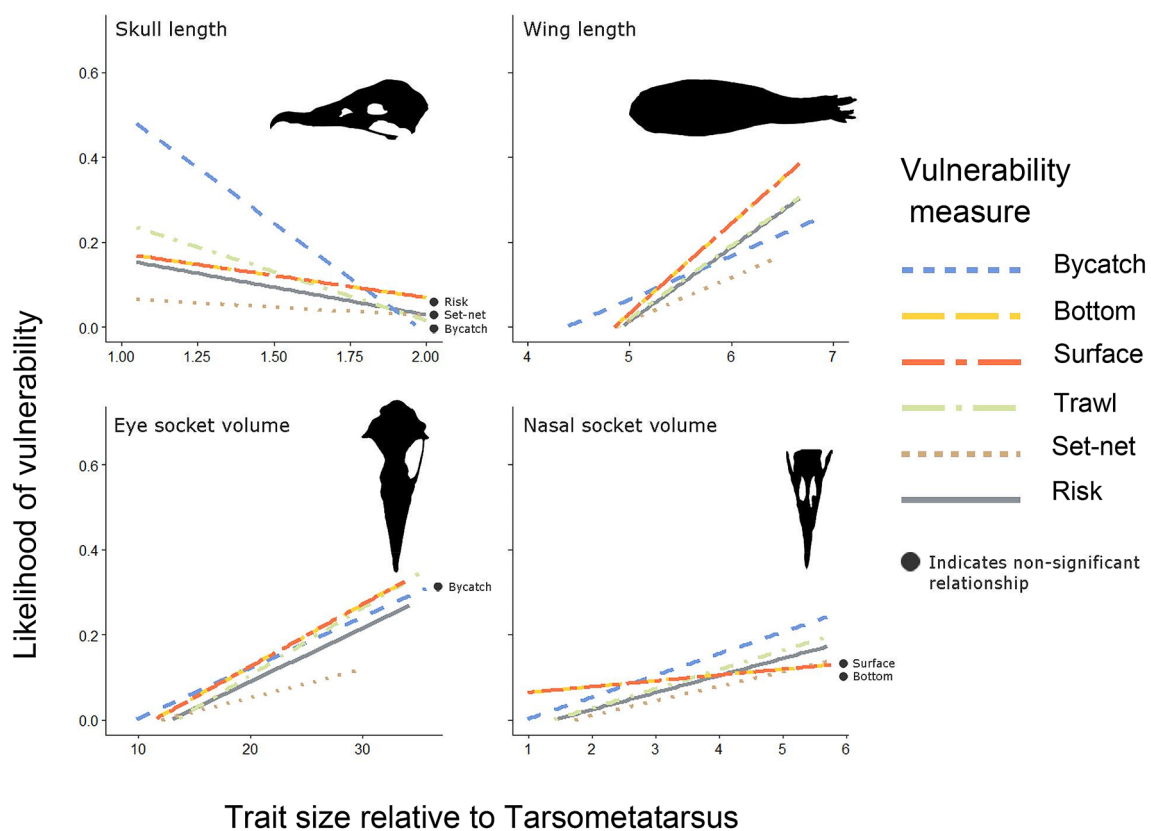


Fig. 3 Sensory and morphological analyses of 6 seabird species caught in New Zealand waters (Buller’s shearwater, fluttering shearwater, common diving petrel, flesh-footed shearwater, sooty shearwater and black petrel) against reported bycatch (a), risk ratio (b), vulnerability to capture in trawl fisheries, c vulnerability to capture in surface longline fisheries, d vulnerability to capture in bottom

longline fisheries, $p < 0.05$, (e) and vulnerability to capture in set-net fisheries (f). Trait size refers to the specific trait i.e. skull length, wing length, eye socket volume and nasal socket volume, relative to the tarsometatarsus. Likelihood of vulnerability is the potential to be caught in trawl, set-net fisheries etc. as well as the risk ratio

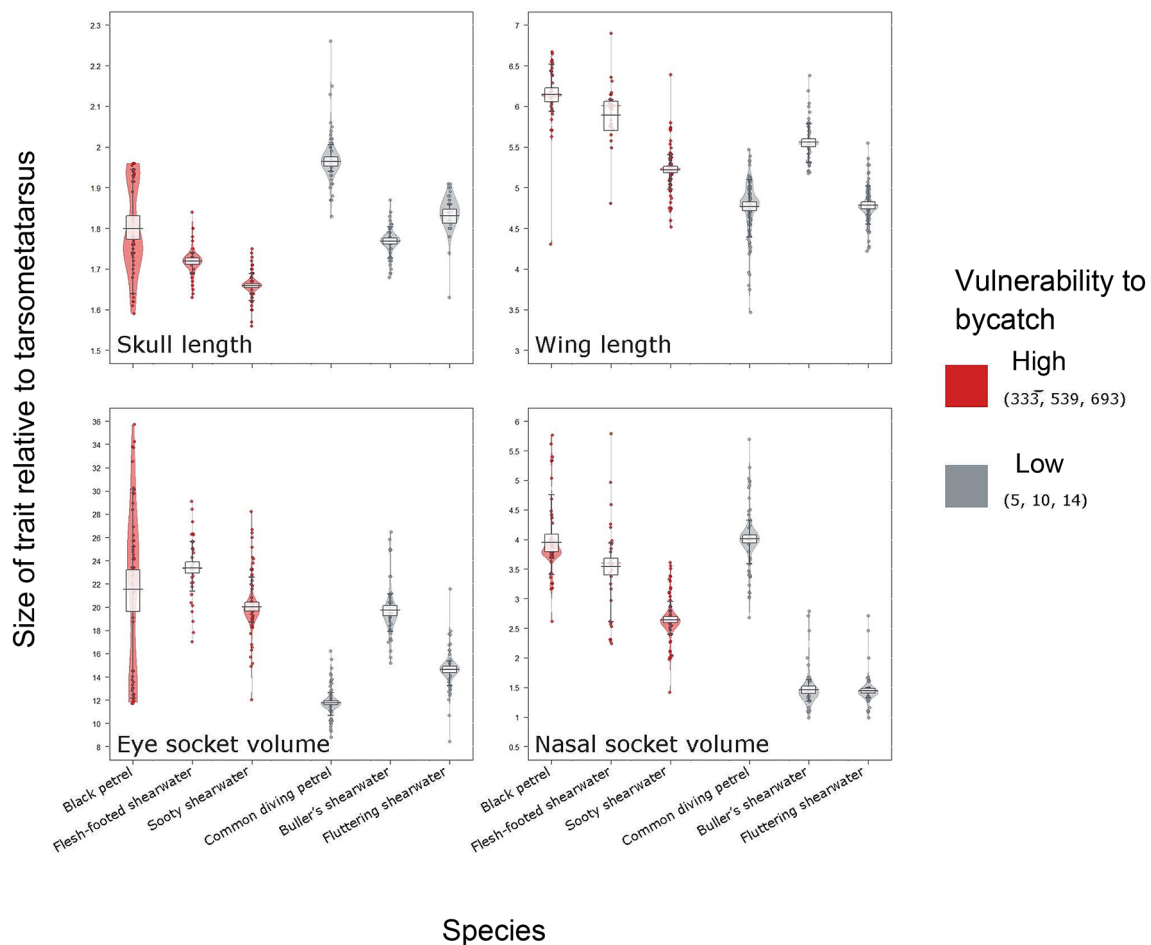


Fig. 4 Sensory and morphological analyses of the 6 seabird species of skull length, wing length, eye socket volume and nostril socket volume (all relative to the tarsometatarsus, raw data plotted). In colour

coded legend, values in parentheses are reported bycatch numbers in New Zealand waters (Richard and Abraham 2013)

behaviour coincides with the location of fishing gear in the water column. Consistent with this, we found that Suliformes (cormorants, boobies and gannets) have a greater vulnerability to capture in surface longline fisheries. The Suliformes tend to have a generalist or fish diet (New Zealand Birds Online; Miskelly 2013; Lyach et al. 2018) and longlines are often baited with pelagic fish and squid depending on the type of fishery (Hoey and Moore, 1999; Robertson et al. 2010). However, our results demonstrate that in general, diet did not correlate with the likelihood of bycatch. It may be that bait matching is likely to be a lesser risk for seabird orders with a more diverse diet, e.g. the Charadriiformes (e.g. gulls) and Sphenisciformes (penguins) which eat a range of fish, squid and crustaceans (Miskelly 2013; Waluda et al. 2017). For these species, the greatest risk is still likely to be geographic overlap with set-nets in their foraging locations (Wilson 1995; Simone et al. 1999; Crawford et al. 2017). Geographic overlap was not analysed in this study but should be examined in

the future, in combination with other fishery and seabird ecology factors.

Burrow nesting seabirds were at a greater risk of becoming bycatch compared to surface nesters. There are known correlations between seabird nest location (burrow or surface), and their dominant foraging mode and sensory ability (Mitkus et al. 2016). Some burrow nesting seabirds use smell for conspecific interactions (Minguez 1996; Jennings and Ebeler 2020), locating mates, chicks or burrows in dimly lit areas (Minguez 1996) and detecting prey and food odours (Malakoff 1999). In contrast, surface nesting seabirds may rely more on a vision for foraging (Mitkus et al. 2016). Generally, surface nesters are larger bodied than burrow nesters (as burrowing possibly constrains maximum body size). Although we found that a larger body size is correlated with a greater risk of becoming bycatch, our dataset indicates that the typically smaller-bodied burrow nesters were more prone to bycatch than the typically large-bodied surface nesters. While body size is an important risk factor for bycatch, this

suggests that other behavioural and potentially sensory factors may contribute.

As predicted, we found that larger seabirds are more at risk of becoming bycatch (c.f. increased capture risk for larger sharks; Frick et al. 2009). This could be because bigger birds have larger gape size and can swallow baited hooks with greater ease (Jiménez et al. 2012). Unfortunately, accurate gape size cannot be obtained from preserved specimens or skulls and very few seabird gape measurements were found in the literature, so we were unable to explore this here. Furthermore, this pattern of increased bycatch risk for birds with larger bodies was consistent for all types of fishing and bycatch, not just fishing methods involving baited hooks. Alternatively, larger body size may correlate with behavioural differences that increase the risk of becoming bycatch. Potentially larger seabirds could also be more dominant and aggressive towards smaller seabirds (Wahl and Heinemann 1979; Hudson and Furness 1989; Friesen et al. 2017; Gianuca et al. 2017), outcompeting them to access bait, and thus becoming bycatch. For example, larger albatrosses were observed dominating smaller shearwaters in pelagic longline fisheries (Jiménez et al. 2012). However, since body size negatively correlated with vulnerability to capture in bottom longline fisheries, other factors are likely influential.

Longer bodies and larger wingspans may increase the risk of entanglement in fishing gear: we found that relatively larger wingspans correlated with increased bycatch in trawl, bottom longline and set-net fisheries. However, it is important to note that larger body sizes and wings do not guarantee a higher number of reported bycatch. Albatrosses are often reported as bycatch and are generally large bodied. For example, Salvin's and white-capped albatross can grow to 950 cm in length (New Zealand Birds Online; Miskelly 2013) and have relatively high reported bycatch in New Zealand waters with 476 Salvin's albatross and 394 white-capped albatross killed between 2007–2011 (Richard and Abraham 2013). In contrast, the black petrel is less than half the size of these albatross (~400 cm; New Zealand Birds Online; Miskelly 2013) but had a much higher reported bycatch of 693 (in 2007–2011; Richard and Abraham 2013). A congener with a similar body size, the cape petrel, *Daption capense*, has a much lower reported bycatch of 125 (Richard and Abraham 2013).

Animals' morphology and sensory systems are under strong selection from their life history, ecology and behaviour (Brewer and Hertel 2007; Mitkus et al. 2016); and in response to the surrounding species and environmental pressures (Walsh 2000). In our larger comparison of 70 seabirds, we found that body size correlated with bycatch. In our smaller study of the skeletons of 6 species, we found that relative to body size, species with relatively larger bills, wings, eyes and nostrils had a greater potential for bycatch.

Bill and wing morphology are under strong and linked selective pressures imposed by foraging behaviour (Hertel and Ballance 1999; Elliott et al. 2013), which also likely imposes strong selection on sensory systems. Larger wings may be more susceptible to net entanglement, or a larger beak and gape may be more prone to becoming hooked as the seabird tries to access the bait (Brothers 1999). However, seabirds with longer wings are also likely to migrate further or have longer foraging trips, which may select for enhanced sensory faculties (e.g. albatrosses; Jouventin and Weimerskirch 1990). Body size and wingspan may be entanglement risks, but also covariates of other life history or sensory factors.

In general, we found evidence that sensory sensitivity interacts with bycatch. We found that species with more sensory pits had a greater risk of becoming bycatch. Shore birds use sensory pits to detect pressure differences exerted by their prey, especially when foraging in situations where vision cannot be used, e.g. certain Charadriiform shorebirds probing and tactile foraging for prey in the sand, and brown kiwi foraging at night (Lourenço et al. 2016; Cunningham et al. 2009; Gutiérrez-Ibáñez et al. 2009). Seabirds forage across vast expanses of ocean and rely on enhanced sensory capability to detect prey beneath the ocean's surface (Nevitt 1999). A greater number of sensory pits suggests increased sensory acuity, and, therefore, greater risk of attraction to fishing vessels.

We found that a larger eye relative to body size correlated with all the bycatch measures. Animals with larger eyes tend to have better vision (Kiltie 2000), so a larger eye socket volume relative to body size likely indicates increased visual capacity to detect fishing operations. Studies show that seabirds are visually attracted to a wide range of visual stimuli associated with fishing. Studies of seabirds such as albatrosses mounted with cameras and GPS loggers reveal there is a strong, long-distance attraction to fishing boats, fish predators such as dolphins or whales, or aggregations of foraging conspecifics (Sakamoto et al. 2009; Thiebault et al. 2014; Tremblay et al. 2014). Attraction to these large visual indicators of fish availability varies with seabird species, but detection distance can be surprisingly far, e.g. 30 km for wandering albatross (Collet et al. 2017). Seabird visual attraction to fishing vessels can be further enhanced with artificial lighting (Merkel and Johansen 2011; Krüger et al. 2017), an additional possible risk-factor for seabirds with larger eyes or more sensitive vision systems.

Seabirds can visually detect fishing boats, fishing equipment such as longlines and set-nets (Collet et al. 2015) and possibly offal discharges or even bait such as squid and fish (Pierre et al. 2013), items that birds catch primarily using their vision. Studies show that seabirds can have extraordinary visual acuity and can detect surprisingly small and specific prey items at sea. Little auks, *Alle alle*, can see and target zones with higher abundances of their preferred

zooplankton prey species, the copepod *Calanus glacialis*, which they prefer to the less energy-rich congener, *Calanus finmarchicus* (Stempniewicz et al. 2013). Although it is not previously reported in the literature, given seabirds' highly sensitive and specialised adaptations for visual foraging, it is highly likely that seabirds with relatively larger eyes are more at risk of becoming bycatch.

We found that seabirds with larger nostrils relative to body size had a higher bycatch risk. Greater olfactory capability could better detect bait and burley, enhancing the risk of attraction and interactions with fisheries. Some seabird species such as Leach's storm petrels, *Oceanodroma leucorhoa*, use olfaction as the main sensory mode for foraging (Mitkus et al. 2018). Olfaction-based foraging can even operate long-distance; other Procellariiformes use olfaction at a landscape scale to detect prey-related chemical odours such as Dimethyl Sulfide (DMS; Nevitt 2008). One outlier species in our study that is inconsistent with this is the common diving petrel. This species has relatively low reported bycatch, yet we found it had the largest nostrils, relative to body size. The large nostril socket volume relative to body size could be a by-product of its diving behaviour, assisting it to withstand dives at great depths (Miskelly 2013; Dunphy et al. 2015). A further challenge is that the six seabird species we measured for our skeletal analyses are all Procellariiformes. These 'tube-nosed' seabirds have some of the largest olfactory bulbs of birds (Cobb 1959, 1960; Bang and Wenzel 1985) and a known reliance on olfaction (e.g. Nevitt 2008). Future studies with a broader taxonomic range of seabirds will be required here.

Our results suggest that in addition to absolute body size and wingspan, the relative size of sensory organs can correlate with bycatch risk, at least for Procellariiformes. Seabirds with larger or more sensitive sensory capacity relative to body size could detect bait and prey items more efficiently compared to those with a less developed sensory system. Larger body sizes may promote entanglement, or ability to travel to boats—but these traits are still likely to be interconnected with, or facilitated by, more sensitive sensory systems that allow birds to see and smell boats and bait at greater distances. Fishing vessels and gear could thus be considered a form of sensory trap, which emits cues that co-opt species' pre-existing behavioural responses to signals (Basolo 1990; Fuller et al. 2010). The association between fishing vessel signals and foraging is likely to be reinforced when seabirds successfully feed from burley, bait or discarded offal or bycatch. However, the risk of injury or becoming bycatch means responding to the cues is no longer adaptive (Christy 1995). A sensory trap context may be a productive new approach for considering bycatch mitigation methods.

Our study used data from the Ministry of Primary Industries, New Zealand (Richard and Abraham 2013).

The risk ratio we used assumes seabirds are land-based populations (Richard and Abraham 2013). We acknowledge the data is not all-encompassing, but it does provide an index for cross-species comparisons despite differences in abundance distribution and fishing differences. It would be ideal to have a more detailed and accurate bycatch data including daily data to address any issues with the uneven distribution of captures, for all seabirds, across various fishing methods and zones. It would also be useful to have data on seabird demography—likely a very productive avenue for future research. We also acknowledge that the data does not take into account the co-occurrence and geographic overlap of the fisheries and seabirds. Data was also limited on recruitment to the fishing sites in terms of the arrival order of the different species. Future research should include greater analysis of the sensory organs including the olfactory bulb, optic tectum, and inner ear, for different seabird species and in other parts of the world.

This is a broad attempt to explore correlations between interconnecting seabird, ecology, morphology and sensory system factors, and to test their links with various measures of marine bycatch. Seabird body size appears to have the strongest effect with a larger size enhancing bycatch. The most at-risk seabirds have relatively smaller skulls and bills but relatively larger wings, eyes and nostrils. Seabird sensory adaptations and sensory ecology could well be an influential factor for bycatch, perhaps explaining the intriguing variation in bycatch rates among co-occurring seabird species, regardless of population size. Morphological, sensory and behavioural traits co-vary and interconnect, and a better understanding of the evolution and function of marine animals' sensory systems could enhance bycatch mitigation strategies.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00227-021-03873-4>.

Acknowledgements We thank Matt Rayner at the Auckland War Memorial Museum/Tāmaki Paenga Hira, Paul Schofield at the Canterbury Museum, and Colin Miskelly at The Museum of New Zealand/Te Papa Tongarewa for providing access to seabird specimens used in the analysis. We would also like to thank Todd Landers (Auckland Council), and reviewers for their suggestions on the manuscript. Greg Holwell provided child care, which was critical for Anne Gaskett's role in this study and manuscript

References

- Abraham E, Richard Y (2017) Assessment of the risk of commercial fisheries to New Zealand seabirds, 2002–03 to 2013–14. Ministry of Primary Industries, New Zealand, pp 1–108
- Baelde P (2001) Fishers' description of changes in fishing gear and fishing practices in the Australian South East trawl fishery. Mar Freshw Res 52(4):411–417

- Bang B, Wenzel B (1985) Nasal cavity and olfactory system. In: King AS, McLelland J (eds) Form and function in birds III. Academic Press, London, pp 195–225
- Barlow J, Cameron G (2003) Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift gill net fishery. *Mar Mamm Sci* 19(2):265–283
- Basolo A (1990) Female preference predates the evolution of the sword in swordtail fish. *Science* 250:808–810
- Blackwell B, Fernandez-Juricic (2013) Behavior and physiology in the development and application of visual deterrents at airports. In: DeVault TL, Blackwell BF, Belant JL (eds) Wildlife in airport environments: preventing animal-aircraft collisions through science-based management. The John Hopkins University Press, Baltimore, pp 11–22
- Bonadonna F, Cunningham G, Jouventin P, Hesters F, Nevitt G (2003) Evidence for nest-odour recognition in two species of diving petrel. *J Exp Biol* 206(20):3719–3722
- Bordino P, Kraus S, Albareda D, Fazio A, Palmerio A, Mendez M, Botta S (2002) Reducing incidental mortality of Franciscana dolphin *Pontoporia blainvillei* with acoustic warning devices attached to fishing nets. *Mar Mamm Sci* 18(4):833–842
- Brewer ML, Hertel F (2007) Wing morphology and flight behavior of pelecaniform seabirds. *J Morph* 268(10):866–877
- Brothers N (1999) The incidental catch of seabirds by longline fisheries: worldwide review and technical guidelines for mitigation. *FAO Fish circ* 937:1–100
- Burns AG. (2019) A Comparison of Circle and J Hook Performance within the Grenadian Pelagic Longline Fishery. Submitted in Partial Fulfillment of the Requirements for the Degree of Masters of Science: Marine Biology. Nova Southeastern University Halmos College of Natural Sciences and Oceanography. pp 7
- Catry P, Dias M, Phillips R, Granadeiro J (2011) Different means to the same end: long-distance migrant seabirds from two colonies differ in behaviour, despite common wintering grounds. *PLoS ONE* 6(10):e26079
- Christy J (1995) Mimicry, mate choice, and the sensory trap hypothesis. *Am Nat* 146(2):171–181
- Clarke S, Sato M, Small C, Sullivan B, Inoue Y, Ochi D (2014) Bycatch in longline fisheries for tuna and tuna-like species: a global review of status and mitigation measures. *FAO Fish Aquac Tech Paper* 588:1–99
- Cobb S (1959) A note on the size of the avian olfactory bulb. *Epilepsia* 1(1–5):394–402
- Cobb S (1960) Observations on the comparative anatomy of the avian brain. *Perspect Biol Med* 3:383–408
- Coggins L, Catalano M, Allen M, Pine W, Walters C (2007) Effects of cryptic mortality and the hidden costs of using length limits in fishery management. *Fish Fisheries* 8(3):196–210
- Collet J, Patrick S, Weimerskirch H (2015) Albatrosses redirect flight towards vessels at the limit of their visual range. *Mar Ecol Prog Ser* 526:199–205
- Collet J, Patrick S, Weimerskirch H (2017) A comparative analysis of the behavioral response to fishing boats in two albatross species. *Behav Ecol* 28(5):1337–1347
- Crawford R, Ellenberg U, Frere E, Hagen C, Baird K, Brewin P, Crofts S, Glass J, Mattern T, Pompert J, Ross K (2017) Tangled and drowned: a global review of penguin bycatch in fisheries. *Endanger Species Res* 34:373–396
- Croxall J, Butchart S, Lascelles B, Stattersfield A, Sullivan B, Symes A, Taylor P (2012) Seabird conservation status, threats and priority actions: a global assessment. *Bird Conserv Int* 22(1):1–34
- Cunningham S, Castro I, Potter M (2009) The relative importance of olfaction and remote touch in prey detection by North Island brown kiwis. *Anim Behav* 78(4):899–905
- Davies R, Cripps S, Nickson A, Porter G (2009) Defining and estimating global marine fisheries bycatch. *Mar Pol* 33(4):661–672
- Dias M, Martin R, Pearmain E, Burfield I, Small C, Phillips R, Yates O, Lascelles B, Borboroglu P, Croxall J (2019) Threats to seabirds: a global assessment. *Biol Conserv* 237:525–537
- Dove A (2015) Foraging and ingestive behaviors of whale sharks, *Rhincodon typus*, in response to chemical stimulus cues. *Biol Bull* 228(1):65–74
- Dunphy B, Taylor G, Landers T, Sagar R, Chilvers B, Ranjard L, Rayner M (2015) Comparative seabird diving physiology: first measures of haematological parameters and oxygen stores in three New Zealand Procellariiformes. *Mar Ecol Prog Ser* 523:187–198
- Elliott K, Ricklefs R, Gaston A, Hatch S, Speakman J, Davoren G (2013) High flight costs, but low dive costs, in auks support the biomechanical hypothesis for flightlessness in penguins. *Proc Natl Acad Sci* 110(23):9380–9384
- Forsell J (1999) Mortality of migratory waterbirds in Mid-Atlantic Coastal anchored gillnets during March and April 1998. Fish and Wildlife Service Chesapeake Bay Field Office Administrative Report, U.S., p 4
- Frick L, Reina R, Walker T (2009) The physiological response of Port Jackson sharks and Australian swellsharks to sedation, gill-net capture, and repeated sampling in captivity. *North Am J Fish Manage* 29(1):127–139
- Friesen M, Beggs J, Gaskett A (2017) Sensory-based conservation of seabirds: a review of management strategies and animal behaviours that facilitate success. *Biol Rev* 92(3):1769–1784
- Fuller R, Noa L, Strellner R (2010) Teasing apart the many effects of lighting environment on opsin expression and foraging preference in bluefin killifish. *Am Nat* 176(1):1–13
- Gallagher A, Orbesen E, Hammerschlag N, Serafy J (2014) Vulnerability of oceanic sharks as pelagic longline bycatch. *Glob Ecol Conserv* 1:50–59
- Gaskin CP, Rayner MJ (2013) Seabirds of the Hauraki Gulf natural history, research and conservation. Hauraki Gulf Forum, p 13
- Gianuca D, Phillips RA, Townley S, Votier SC (2017) Global patterns of sex- and age-specific variation in seabird bycatch. *Biol Cons* 205:60–76
- Gutiérrez-Ibáñez C, Iwaniuk A, Wylie D (2009) The independent evolution of the enlargement of the principal sensory nucleus of the trigeminal nerve in three different groups of birds. *Brain Behav Evol* 74(4):280–294
- Hauraki Gulf Forum (2020) State of our Gulf 2020. Hauraki Gulf Marine Park, Hauraki Gulf Form, Auckland Council, Auckland, pp 1–91
- Haverkamp A, Hansson B, Knaden M (2018) Combinatorial codes and labeled lines: how insects use olfactory cues to find and judge food, mates, and oviposition sites in complex environments. *Front Physiol* 9:49
- Hayes B, Brooke M (1990) Retinal ganglion-cell distribution and behavior in procellariiform seabirds. *Vision Res* 30:1277–1289
- Hertel F, Ballance L (1999) Wing ecomorphology of seabirds from Johnston Atoll. *Condor* 101(3):549–556
- Hoey J, Moore N (1999). Captain's report: multi-species characteristics for the US Atlantic pelagic longline fishery. National Fisheries Institute Report to NOAA, National Marine 544 Bul Mar Sci 88(3). 2012 Fisheries Service, Silver Spring, MD, USA. Available from: <http://www.sefsc.noaa.gov/seaturtlecontractreports.js>. Accessed 17 June, 2020
- Hudson A, Furness R (1989) The behaviour of seabirds foraging at fishing boats around Shetland. *Ibis* 131(2):225–237
- Huse I, Løkkeborg S, Soldal AV (2002) Relative selectivity in trawl, longline and gillnet fisheries for cod and haddock. *ICES JI MarSci* 57(4):1271–1282
- IUCN (2019) The IUCN red list of threatened species. Version 2019–1. <https://www.iucnredlist.org>. Downloaded on 26 July 2019.
- Jennings SL, Ebeler SE (2020) Individual chemical profiles in the leach's storm-petrel. *J Chem Ecol* 28:1–20

- Jiménez S, Domingo A, Abreu M, Brazeiro A (2012) Bycatch susceptibility in pelagic longline fisheries: are albatrosses affected by the diving behaviour of medium-sized petrels? *Aquat Conserv: Mar Freshw Ecosyst* 22(4):436–445
- Johnson N, Siefkes M, Li W (2005) Capture of ovulating female sea lampreys in traps baited with spermiating male sea lampreys. *North Am J Fish Manage* 25(1):67–72
- Jouventin P, Weimerskirch H (1990) Satellite tracking of wandering albatrosses. *Nature* 343(6260):746
- Jouventin P, Aubin T, Lengagne T (1999) Finding a parent in a king penguin colony: the acoustic system of individual recognition. *Anim Behav* 57(6):1175–1183
- Kiltie RA (2000) Scaling of visual acuity with body size in mammals and birds. *Func Ecol* 14(2):226–234
- Krüger L, Paiva VH, Petry MV, Ramos JA (2017) Strange lights in the night: using abnormal peaks of light in geolocator data to infer interaction of seabirds with nocturnal fishing vessels. *Polar Biol* 40(1):221–226
- Lequette B, Verheyden C, Jouventin P (1989) Olfaction in subantarctic seabirds: its phylogenetic and ecological significance. *Condor* 91(3):732–735
- Lewison R (2004) Understanding impacts of fisheries bycatch on marine megafauna. *Trends Ecol Evol* 19(11):598–604
- Lewison R, Crowder L, Wallace B, Moore J, Cox T, Zydelski R, McDonald S, DiMatteo A, Dunn D, Kot C, Bjorkland R (2014) Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. *Proc Natl Acad Sci* 111:5271–5276
- Li W, Scott A, Siefkes M, Yan H, Liu Q, Yun S, Gage D (2002) Bile acid secreted by male sea lamprey that acts as sex pheromone. *Science* 296:138–141
- López B, Shirai J (2007) Bottlenose dolphin (*Tursiops truncatus*) presence and incidental capture in a marine fish farm on the north-eastern coast of Sardinia (Italy). *J Mar Biol Assoc UK* 87(1):113–117
- Lourenço PM, Catry T, Piersma T, Granadeiro JP (2016) Comparative feeding ecology of shorebirds wintering at Banc d'Arguin. *Mauritania Estuar coast* 39(3):855–865
- Lyach R, Blabolil P, Čech M (2018) Great Cormorants *Phalacrocorax carbo* feed on larger fish in late winter. *Bird Study* 65(2):249–256
- Madliger C (2012) Toward improved conservation management: a consideration of sensory ecology. *Biodivers Conserv* 21(13):3277–3286
- Malakoff D (1999) Following the scent of avian olfaction. *Sci* 286(5440):704–705
- Merkel FR, Johansen KL (2011) Light-induced bird strikes on vessels in Southwest Greenland. *Mar Poll Bull* 62(11):2330–2336
- Minguez E (1996) Olfactory nest recognition by British storm-petrel chicks. *Anim Behav* 53(4):701–707
- Miskelly C (2013) New Zealand Birds online—the digital encyclopedia of New Zealand birds. nzbirdsonline.org.nz/. Accessed 10 July 2019.
- Mitkus M, Nevitt G, Danielsen J, Kelber A (2016) Vision on the high seas: spatial resolution and optical sensitivity in two procellariiform seabirds with different foraging strategies. *J Exp Biol* 219(21):3329–3338
- Mitkus M, Nevitt G, Kelber A (2018) Development of the visual system in a burrow-nesting seabird: leach's storm petrel. *Brain Behav Evol* 91(1):4–16
- Nelson J, Baird P (2001) Seabird communication and displays. In: Schreiber EA, Burger J (eds) *Biology of marine birds*. CRC Press, Boca Raton, FL, pp 307–358
- Nevitt G (1999) Olfactory foraging in Antarctic seabirds: a species-specific attraction to krill odors. *Mar Ecol: Prog Ser* 177:235–241
- Nevitt G (2008) Sensory ecology on the high seas: the odor world of the procellariiform seabirds. *J Exp Biol* 211(11):1706–1713
- Oehlmann J, Schulte-Oehlmann U, Kloas W, Jagnytsch O, Lutz I, Kusk K, Wollenberger L, Santos E, Paull G, Van Look K, Tyler C (2009) A critical analysis of the biological impacts of plasticizers on wildlife. *Philos Trans Royal Soc B: Biol Sci* 364(1526):2047–2062
- Piatt J, Wetzel J, Bell K, DeGange A, Balogh G, Drew G, Geernaert T, Ladd C, Byrd G (2006) Predictable hotspots and foraging habitat of the endangered short-tailed albatross (*Phoebastria albatrus*) in the North Pacific: Implications for conservation. *Deep Sea Res Part II* 53(3–4):387–398
- Pierre J, Goad D, Thompson F, Abraham E (2013) Reducing seabird bycatch in bottom-longline fisheries. Department of Conservation, Wellington, pp 1–59
- Plenderleith M, Oosterhout C, Robinson R, Turner G (2005) Female preference for conspecific males based on olfactory cues in a Lake Malawi cichlid fish. *Biol Lett* 1(4):411–414
- Poot H, Ens B, de Vries H, Donners M, Wernand M, Marquenie J (2008) Green light for nocturnally migrating birds. *Ecol Soc* 13(2):47
- Reeves R, McClellan K, Werner T (2013) Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endanger Species Res* 20(1):71–97
- Richard Y, Abraham E (2013) Risk of commercial fisheries to New Zealand seabird populations. New Zealand aquatic biodiversity report 109. Ministry of Fisheries, Wellington, New Zealand, pp 1–58
- Robertson G, Candy S, Wienecke B (2010) Effect of line shooter and mainline tension on the sink rates of pelagic longlines and implications for seabird interactions. *Aquat Conserv: Mar Freshw Ecosyst* 20(4):419–427
- Rodríguez A, Rodríguez B, Negro J (2015) GPS tracking for mapping seabird mortality induced by light pollution. *Sci Rep* 5:10670
- Rodríguez A, Holmes N, Ryan P, Wilson K, Faulquier L, Murillo Y, Raine A, Penniman J, Neves V, Rodríguez B, Negro J (2017) Seabird mortality induced by land-based artificial lights. *Cons Biol* 31(5):986–1001
- RStudio Team (2016) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <http://www.R-project.org/>
- Ryan M, Cummings M (2013) Perceptual biases and mate choice. *Ann Rev Ecol Evol Syst* 44:437–459
- Sakamoto KQ, Takahashi A, Iwata T, Trathan PN (2009) From the eye of the albatrosses: a bird-borne camera shows an association between albatrosses and a killer whale in the Southern Ocean. *PLoS ONE* 4(10):e7322
- Schuyler Q, Wilcox C, Townsend K, Hardesty B, Marshall N (2014) Mistaken identity? Visual similarities of marine debris to natural prey items of sea turtles. *BMC Ecol* 14(1):14
- Senar J, Pascual J (1997) Keel and tarsus length may provide a good predictor of avian body size. *Ardea-Wageningen* 85:269–274
- Shealer D (2002) Foraging behavior and food of seabirds. *Biol Mar Birds* 137–177
- Simeone A, Bernal M, Meza J (1999) Incidental mortality of Humboldt penguins *Spheniscus humboldti* in gill nets, central Chile. *Mar Ornithol* 27:157–161
- Stempniewicz L, Darecki M, Trudnowska E, Błachowiak-Samołyk K, Boehnke R, Jakubas D, Keslinka-Nawrot L, Kidawa D, Sagan S, Wojczulanis-Jakubas K (2013) Visual prey availability and distribution of foraging little auks (*Alle alle*) in the shelf waters of West Spitsbergen. *Pol Biol* 36(7):949–955
- Suryan R, Dietrich K, Melvin E, Balogh G, Sato F, Ozaki K (2008) Migratory routes of short-tailed albatrosses: use of exclusive

- economic zones of North Pacific Rim countries and spatial overlap with commercial fisheries in Alaska. *Biol Cons* 137(3):450–460
- Thiebault A, Mullers R, Pistorius P, Tremblay Y (2014) Local enhancement in a seabird: reaction distances and foraging consequence of predator aggregations. *Behav Ecol* 25(6):1302–1310
- Thomsen F, Lüdemann K, Kafemann R, Piper W (2006) Effects of offshore wind farm noise on marine mammals and fish. Biola, Hamburg, Germany on behalf of COWRIE Ltd 62:1–62
- Tremblay Y, Thiebault A, Mullers R, Pistorius P (2014) Bird-borne video-cameras show that seabird movement patterns relate to previously unrevealed proximate environment, not prey. *PLoS ONE* 9(2):e88424
- Tull C, Germain A, May W (1972) Mortality of thick-billed murre in the west Greenland salmon fishery. *Nat* 237:42–44
- Vincent S, Shine R, Brown G (2005) Does foraging mode influence sensory modalities for prey detection in male and female file-snakes, *Acrochordus arafurae*? *Anim Behav* 70(3):715–721
- Votier S, Bicknell A, Cox S, Scales K, Patrick S (2013) A bird's eye view of discard reforms: bird-borne cameras reveal seabird/fishery interactions. *PLoS ONE* 8(3):e57376
- Wagner E, Boersma P (2011) Effects of fisheries on seabird community ecology. *Rev Fish Sci* 19(3):157–167
- Wahl T, Heinemann D (1979) Seabirds and fishing vessels: co-occurrence and attraction. *Condor* 81(4):390–396
- Walsh D (2000) Chasing shadows: natural selection and adaptation. *Stud Hist Philos Sci Part C: Stud Hist Philos of Biol Biomed Sci* 31(1):135–153
- Waluda CM, Hill SL, Peat HJ, Trathan PN (2017) Long-term variability in the diet and reproductive performance of penguins at Bird Island. *South Georgia Mar Biol* 164(3):39
- Ward P, Myers R (2005) Inferring the depth distribution of catchability for pelagic fishes and correcting for variations in the depth of longline fishing gear. *Can J Fish Aquat Sci* 62(5):1130–1142
- Wilson P (1995) Foraging ecology. In: Williams TD (ed) *The penguins Spheniscidae*. Oxford University Press, Oxford, pp 81–10
- Žydelis R, Small C, French G (2013) The incidental catch of seabirds in gillnet fisheries: a global review. *Biol Cons* 162:76–88

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.