

Variation in live-capture rates of albatrosses and petrels in fisheries, post-release survival and implications for management



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ABSTRACT

Bycatch of seabirds in longline fisheries includes mortalities and live captures (mainly during hauling). Excluding outliers, the latter accounts for 5–70% (mean 40.4%) of all bycaught birds in demersal, and 3–23% (mean 10.7%) in pelagic longline fisheries. The proportion that later die from injuries is unknown, and this cryptic mortality complicates efforts to quantify fisheries impacts. Over a 26-year period at South Georgia, foul-hooking indices - birds with embedded hooks or entangled among tens of thousands checked at the colony - were broadly similar in wandering albatrosses *Diomedea exulans* and giant petrels *Macronectes* spp., an order of magnitude lower in black-browed albatrosses *Thalassarche melanophris* and nil in two other albatross species. This likely reflected differing degrees of overlap with fisheries and interaction with gear during hauling. Indices peaked in the early-mid 2000s, then declined, broadly corresponding with changing fishing practices, including the lagged effect of a seasonal fisheries-closure, introduction of a new fishing system, reduced effort in some demersal fisheries and general improvements in bycatch mitigation. Foul-hooking indices at colonies can therefore reflect relative risk for different species over time, and be a useful adjunct to vessel-based monitoring of live-capture rates. Taking into account age and status when reported, and annual survival probabilities, subsequent survival of live-caught and released wandering albatrosses was around 40% of that expected for the wider population. This has major implications for ecological risk assessments that seek to determine the impacts of fisheries on seabirds, as most do not currently consider deleterious impacts of live capture.

1. Introduction

Worldwide, many marine predators are declining because of unsustainable levels of incidental mortality (bycatch) in fisheries (Lewison et al., 2004; Phillips et al., 2016). Longlining and gillnetting kills an estimated 160,000 and 400,000 seabirds, respectively, per year (Anderson et al., 2011; Žydelis et al., 2013). Global seabird mortality in trawl or artisanal fisheries has not been estimated, but given the high rates in many regions (Favero et al., 2010; Maree et al., 2014; Sullivan et al., 2006), is likely of a similar order. Among the worst affected are albatrosses and large petrels, which are vulnerable because of their extreme life-histories. They reproduce for the first time aged 5–10+ years, have a single-egg clutch and some are biennial breeders if successful, raising one chick at most every two years (Warham, 1990). They are also highly pelagic and so encounter fisheries in multiple jurisdictions (Clay et al., 2019; Phillips et al., 2006; Thiers et al., 2014). Recognising the need for a concerted international response to understand and mitigate their threats, a dedicated treaty, the Agreement on the Conservation of Albatrosses and Petrels (ACAP) was ratified in 2004

(Phillips et al., 2016).

Various methodologies that reduce seabird bycatch in fisheries have been developed over the last 1–2 decades (Gilman et al., 2014; Løkkeborg, 2011; Melvin et al., 2014; Robertson et al., 2018; Sullivan et al., 2018). Although increasingly implemented, particularly in national waters, mandatory bycatch-mitigation measures are frequently far from best practise, and monitoring of compliance and bycatch rates remains inadequate, particularly in the High Seas (Phillips, 2013; Phillips et al., 2016). In longlining, most seabird bycatch occurs during setting, when scavengers attracted to bait either swallow the hook or are entangled, then dragged underwater and drowned (Brothers et al., 2010; Jimenez et al., 2014). However, substantial numbers may also be entangled or hooked in the bill, gape, wing, leg or body during line hauling or, more rarely, at the end of setting, and brought onto the vessel alive (Brothers, 2016; Gilman et al., 2014). Recommended best-practise seabird bycatch mitigation in longline fisheries involves the simultaneous use of streamer (tori) lines to discourage attacks on baited hooks, greater line-weighting to sink hooks rapidly beyond diving depths, and night setting to reduce risk to albatrosses and other species

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Table 1
Proportion of bycaught seabirds in different fisheries that are caught alive.

Fishery type	Region (fleet ^a)	Years	Proportion caught alive and released ^b	Reference
Pelagic longline	Uruguay (Japan)	2009–2011	11% (<i>Diomedea</i> spp. only)	(Jimenez et al., 2014)
Pelagic longline	Uruguay	1998–2004, 2004–2011	3% (all birds), 6% (<i>Diomedea</i> spp. only)	(Jiménez et al., 2009; Jimenez et al., 2014)
Pelagic longline	South Atlantic Ocean (Taiwan)	2004–2008	12%	(Yeh et al., 2013)
Pelagic longline	South Africa and adjacent High Seas	2006–2013	11%	(Rollinson et al., 2017)
Pelagic longline	Australia (Japan)	1988–1995	3%	(Gales et al., 1998)
Pelagic longline	New Zealand	2006/07 to 2014/15	23%	(Richard et al., 2017)
Pelagic longline	Pacific Ocean, predominantly northwest (Taiwan)	2002–2007	12%	(Huang and Yeh, 2011)
Pelagic longline	Hawaii	2004–2012	75%	(Gilman et al., 2014)
Demersal (artisanal) longline	Chile	1999	90% ^c	(Moreno et al., 2006)
Demersal longline	Falklands	2002–2004	70%	(Oley et al., 2007b)
Demersal longline	South Georgia	1996–2006	46%	(Varty et al., 2008)
Demersal longline	South Africa	2000–2006	62%	(Petersen et al., 2009)
Demersal longline	Namibia	2006	5%	(Petersen et al., 2009)
Demersal longline	New Zealand	2006/07 to 2014/15	19%	(Richard et al., 2017)

^a Fleet indicated only if different from region.

^b Based on all species unless indicated otherwise.

^c Overall seabird bycatch rate very low.

that mainly forage in daylight (Agreement on the Conservation of Albatrosses and Petrels, 2017). With an increasing number of fisheries adopting this last measure during setting, the proportion of branch lines hauled in daylight may increase, with the unintended consequence of more live captures (Brothers, 2016; Gilman et al., 2016).

Monitoring of live captures is patchy and incomplete, but rates reported for various demersal and pelagic longline fisheries range from 3 to 90% (Table 1). Most birds are probably released alive by crew, often by cutting the line which leaves the hook embedded. This may have a variety of sublethal effects (Wilson et al., 2014). Critically, the proportion that later die of their injuries is unknown, and this cryptic mortality is a major complication when trying to quantify impacts of bycatch on seabird populations (Richard et al., 2017). Here we examine two sources of information on live captures: reports of albatrosses and petrels ringed at South Georgia that were caught during fishing operations and released alive, together with their ringing and resighting histories, and; observations of birds seen at the breeding colony with embedded hooks or entangled in line. The aims of the study were to: (i) determine the relative risk of live capture for different species of albatrosses and petrels breeding at South Georgia; (ii) check for trends in rates of live capture over time; (iii) determine subsequent survival rate of live-caught birds relative to the wider population; and; (iv) discuss the implications in terms of impacts of live captures on seabird populations and recommended improvements to monitoring and management.

2. Materials and methods

2.1. Ring resightings

Reports were obtained from the ringing authority (British Trust for Ornithology) of ringed seabirds from Bird Island, South Georgia (54°00'S, 38°03'W). These were filtered for finding circumstances coded as released alive (codes XP or XT). If the associated activity was given as "Fishing" or "Longline", or the release location was far from land in known fishing areas, the capture was assumed to be during fishing operations. Fishery type (pelagic longline, demersal longline or other) was provided in the ring report or inferred from capture location based on maps of fishing effort in Tuck et al. (2003) and consultation with regional experts. A few birds with release locations on or < 1 km from the coast were excluded even if the activity was "Fishing" in case of misinterpretation by the submitter, although they may have been caught in near-shore recreational or artisanal fisheries, or found on

beaches hooked or entangled in line. None of these birds were seen back at the colony, so if included would have resulted in lower estimated survival rates (see below).

The earliest ringing at Bird Island was in austral summer 1958/59. Intensive annual monitoring (including ringing) of black-browed *Thalassarche melanophris* and grey-headed albatrosses *T. chrysostoma* in selected subcolonies, and of all wandering albatrosses *Diomedea exulans* on the island began in summer 1975/76 and 1979/80, respectively (Pardo et al., 2017). Monitoring of northern *Macronectes halli* and southern giant petrels *M. giganteus* took place in 1978/79–1980/81, was then intermittent, and became annual in a well-demarcated study area in 2002/03 (Brown et al., 2015; Hunter, 1984). Ringing records were used to determine the age of birds captured and released alive (hereafter 'live-caught') in fisheries, and a full breeding history was available for any bird that bred in the intensive study colonies.

Bird Island holds 60% of wandering albatrosses at South Georgia (Poncet et al., 2006), and the rate of emigration of ringed birds to other islands in the group is negligible (Pardo et al., 2017). A simple model was used to compare survival rates of live-caught birds with those of the wider population, based on mean annual survival of 85% for juveniles aged up to four years, and of 94% for immatures and adults, calculated from 21,900 encounter histories (Pardo et al., 2017). This comparison accounted for possible delays before a released bird would be resighted of (i) two years for adults, as wandering albatrosses breed biennially if successful, and (ii) the interval between age at live-capture of juveniles and immatures, and mean age of first breeding (recruitment) of 10.5 years (Croxall et al., 1998). Three wandering albatrosses that were live-caught in 1969–1972 were excluded from this analysis, as they could have recruited before the start of intensive annual monitoring, and not been resighted for that reason.

2.2. Colony-based monitoring of entanglements

Annual monitoring of albatrosses and petrels entangled in fishing gear (hereafter 'foul-hooked') began at Bird Island in summer 1992/93. Data from then until 2008/09 were summarised in Phillips et al. (2010). These birds carried hooks in the foot, leg, wing, bill or throat, and, whenever possible, were captured and the gear removed. Chicks with line protruding from the bill were excluded from analysis, as this results from ingestion of hooks in non-target fish discarded by crew. By comparison, this will rarely, if ever, be the source of protruding line in adults, as they can readily regurgitate a hook that is not embedded during hauling (Phillips et al., 2010). The few birds with rope or twine

around the tarsus were also excluded as this may have resulted from entanglement with floating debris.

Annual “foul-hooking indices” were calculated for each species as the total number of foul-hooked birds observed, divided by sampling effort. As foul-hooking is obvious from a protruding hook or trailing line, indicative sampling effort was considered to be twice the number of nests in intensively-studied subcolonies (both partners ringed; nests visited daily to weekly throughout breeding), in addition to the number of nests in subcolonies visited once only during incubation to count nesting pairs (only one partner checked). For giant petrels, we also included a probable maximum of 1000 other birds seen scavenging on beaches or during unrelated fieldwork activities. This accounts for long-term changes in population sizes at Bird Island; the albatrosses are decreasing (Poncet et al., 2006; Poncet et al., 2017), whereas northern and southern giant petrels are, respectively, increasing slowly or stable (Gianuca et al., 2019). Visual inspection indicated that changes in foul-hooking indices over time were non-linear, and for wandering albatrosses and giant petrels were suggestive of increases until the early-mid 2000s, and decreases thereafter. Breakpoints in the relationships with year were therefore tested by fitting piecewise, 2-segment linear regressions in Sigmaplot v. 14.0.

3. Results

3.1. Ring reports

In total, two black-browed albatrosses, five northern giant petrels and 22 wandering albatrosses were reported as live-caught in fisheries

Table 2

Records of ringed albatrosses and petrels from Bird Island (South Georgia) caught and released alive in fisheries. Juv = Juvenile (< 4 years); Imm = Immature (4–11 years); Ad = Adult (breeding or > 11 years); Ch = Chick; Br = breeder; Nbr = nonbreeder. PLL = pelagic longline; DLL = demersal longline; Pot = pot (creel). BBA = black-browed albatross; NGP = northern giant petrel; WA = wandering albatross.

Species	Ring	Age class at ringing	Ringling date	Live-capture date	Live-capture location	Likely fishery	Age-class - status (age in years ^a) when live-caught	Bred prior to live capture ^c	Bred after live capture ^c
BBA	56825999	Ch	09-Mar-63	02-Oct-65	North Cape (NZ)	PLL	Juv (2.7)	n/a	n/a
BBA	1146085	Ch	16-Apr-84	15-Feb-15	Great Australian Bight	Pot	Ad - Nbr (31.1)	√	√
NGP	5055480	Ch	01-Feb-73	07-Jun-73	East Pacific	PLL	Juv (0.5)	n/a	n/a
NGP	1131044	Ad	31-Oct-78	26-Aug-02	Falklands	DLL	Ad	n/a	n/a
NGP	1436026	Ch	03-Mar-09	06-May-09	New Zealand	PLL	Juv (0.4)	n/a	n/a
NGP	1447504	Ch	07-Mar-10	15-Nov-10	Chile	DLL	Juv (1.0)	n/a	n/a
NGP	1442472	Ch	03-Mar-14	15-Jun-14	Central Pacific	PLL	Imm (4.5)	n/a	n/a
WA	52872193	Ad	12-Mar-61	14-Oct-69	SE Atlantic	PLL	Ad	n/a	n/a
WA	52875847	Ad	03-Jan-63	21-Oct-69	SE Atlantic	PLL	Ad	n/a	n/a
WA	52871312	Ad	14-Feb-61	18-Oct-72	SE Atlantic	PLL	Ad	n/a	n/a
WA	5077733	Ch	04-Nov-76	27-Jul-79	Patagonian Shelf	n/a ^b	Juv (3.4)		
WA	5117339	Ch	06-Oct-85	24-Mar-87	SW Chile	DLL	Juv (2.0)		
WA	5117112	Ch	22-Oct-84	14-Feb-87	East of Tasmania	PLL	Juv (2.9)		√
WA	5108744	Ch	03-Nov-81	22-Mar-89	Shag Rocks	DLL	Imm (8.0)		
WA	5077562	Ch	01-Nov-76	07-Aug-89	Patagonian Shelf	PLL	Ad - Nbr (13.4)	√	√
WA	5116287	Ch	09-Oct-84	22-Jun-90	NZ East Cape	PLL	Imm (6.3)		
WA	5098094	Ch	29-Oct-81	26-Aug-90	SW Atlantic	PLL	Ad - Br (9.5)	√	
WA	5146231	Ch	18-Oct-92	02-Jul-94	Patagonian Shelf	DLL	Juv (2.3)		√
WA	5143042	Ad	26-Jan-89	03-May-95	Patagonian Shelf	DLL	Ad - Nbr	√	
WA	5132429	Ch	04-Oct-89	08-Mar-96	South Georgia	DLL	Ad - Br (7.0)	√	√
WA	5156082	Ch	17-Sep-95	08-May-97	Chile	DLL	Juv (2.2)		
WA	5144341	Ch	1988	08-May-97	Chile	DLL	Ad - Nbr (9.2)	√	√
WA	5164394	Ch	17-Sep-95	03-Mar-98	Chile	DLL	Juv (3.0)		
WA	5187350	Ch	15-Oct-98	05-Dec-98	Chile	DLL	Juv (0.7)		
WA	5184659	Ch	14-Oct-97	26-Sep-99	Chile	DLL	Juv (2.5)		
WA	5122444	Ch	30-Oct-86	15-Oct-00	Southeast Brazil	PLL	Ad - Br (14.6)	√	
WA	5132322	Ad	28-Dec-88	15-Nov-02	East Indian Ocean	PLL	Ad - Nbr	√	
WA	5217738	Ad	11-Feb-02	03-Jan-04	Burdwood Bank	DLL	Ad	√	
WA	4002703	Ch	16-Aug-07	21-Dec-07	East Argentine Basin	PLL	Juv (0.8)		

^a For birds ringed as chicks, age based on mean hatch date for each species (30 Nov., 3 Jan. and 11 March for northern giant petrel, black-browed albatross and wandering albatross, respectively).

^b Both demersal longline and trawl fisheries operate in capture area.

^c Monitoring only comprehensive for wandering albatrosses since 1980.

between 1961 and 2015 (Table 2). Capture locations were widely distributed and included operational areas of multiple national fleets (Fig. 1, Table 2). For the species with the largest sample size, the wandering albatross, similar numbers (4 to 7 individuals) were reported as live-caught in each year-quarter. Based on information in the reports and location, two northern giant petrels and 11 wandering albatrosses were captured in demersal longline and one black-browed albatross, three northern giant petrels and 10 wandering albatrosses in pelagic longline fisheries, one black-browed albatross in a pot fishery, and one wandering albatross in the operational area of both demersal longline and trawl fisheries (Table 2). The earliest records of live-capture were in pelagic longline fisheries, including three wandering albatrosses southwest of South Africa in 1969–72, and one black-browed albatross off New Zealand in 1965. Subsequent records were giant petrels and wandering albatrosses live-caught in demersal longline fisheries off Chile, on the Patagonian Shelf and around South Georgia, and in pelagic longline fisheries in the Atlantic, Indian and Pacific oceans, and off New Zealand.

Considering only the live-captures in longline fisheries, the overall annual reporting rate from 1965 to 2018 was 0.50 (27 birds in 54 years; Table 2). There appears to be four phases; (i) five birds reported in 1965 to 1973 (0.56 birds/year; all in pelagic longline), (ii) none reported in 1974 to 1986, (iii) 21 birds in 1987 to 2010 (0.88 birds/year; demersal and pelagic longline), and (iv) one bird in 2011 to 2018 (0.13 birds/year). The ratio of subadults (juveniles and immatures), to adults, was 4:1 for giant petrels (total $n = 5$) and 1:1 for wandering albatrosses ($n = 22$). The mean age \pm SD of the subadult wandering albatrosses when live-caught was 3.1 ± 2.1 years (range 0.74 to 8.0 years). None

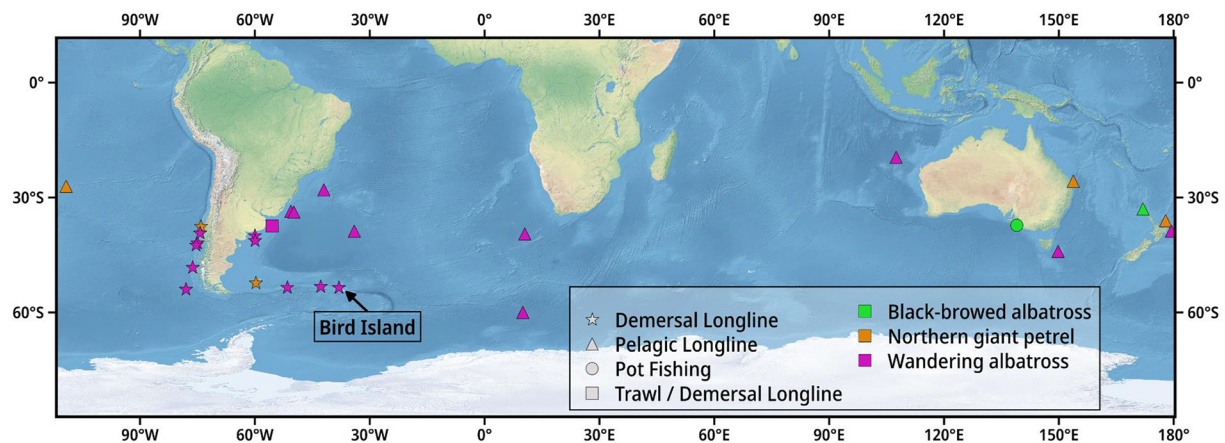


Fig. 1. Location of live-captures of ringed wandering and black-browed albatrosses, and northern giant petrels from Bird Island, South Georgia from 1965 to 2015, and associated fishery type.

of the 11 wandering albatrosses live-caught as a subadult had been seen at the colony since ringing, and only two were seen subsequently as breeders. All eight wandering albatrosses live-caught as adults had bred previously, and three were seen subsequently (all as breeders). Based on the age of the subadults when live-caught and assuming the same survival probabilities and recruitment age as in the wider population (see methods), 6.2 individuals would be expected to survive to breed. Based on the survival probability for adults, 7.1 of the 8 live-caught adults would be expected to survive two years. However, only 5 birds (38%; see Table 2) were seen out of the total of 13 that might be expected.

3.2. Entangled (foul-hooked) birds at colonies

Over the 26-year study, 45 adult wandering albatross, 7 black-browed albatrosses and 30 giant petrels (13 northern giant petrels, 11 southern giant petrels and six unknown), and no grey-headed or light-mantled albatrosses *Phoebastria palpebrata*, were seen foul-hooked at Bird Island (Table 3). All incidents involved longline gear. Foul-hooked wandering albatrosses and giant petrels were recorded in most years. Over the whole study period, foul-hooking indices were broadly similar in wandering albatrosses and giant petrels, an order of magnitude lower in black-browed albatrosses, and nil in grey-headed and light-mantled albatrosses (Fig. 2). The foul-hooking indices for each species changed over time, increasing from the mid to late 1990s to peaks in the early-mid 2000s, and declining thereafter, particularly in recent years (Fig. 2). For black-browed albatrosses, there was no obvious trend until 2005, but thereafter no foul-hooked birds were seen. Piecewise 2-segment linear regressions identified breakpoints indicating a shift from a positive to negative relationship with year in 2001 and 2005, respectively, for giant petrels (ANOVA $F_{4, 22} = 11.2, P < 0.0001$) and wandering albatrosses (ANOVA $F_{4, 22} = 12.3, P < 0.0001$).

4. Discussion

4.1. Differences among species and contributing factors

Based on foul-hooking indices at the colony (i.e. number of hooked or entangled birds observed, relative to sampling effort), the rates of live-capture of wandering albatrosses and giant petrels were broadly similar, an order of magnitude lower in black-browed albatrosses, and nil in grey-headed and light-mantled albatrosses over the 26 year study (1992/93 to 2017/18). The live-captures of ringed birds reported from fisheries involved the same species, but numbers cannot be converted to species-specific rates because of reporting biases, as crew or observers of particular fleets may rarely or never report rings.

Although < 100 light-mantled albatrosses are checked each year, it

Table 3

Number of adults recorded foul-hooked (entangled by fishing gear) at Bird Island, South Georgia in austral summers 1992/1993–2017/2018.

	Wandering albatross	Black-browed albatross	Giant petrels
1992/1993	1	1	0
1993/1994	1	1	1
1994/1995	1	0	0
1995/1996	4	1	0
1996/1997	1	0	3
1997/1998	0	0	0
1998/1999	1	1	3
1999/2000	2	0	2
2000/2001	6	0	3
2001/2002 ^a	4	2	2
2002/2003	1	0	5
2003/2004	1	1	2
2004/2005	3	0	1
2005/2006	2	0	2
2006/2007	3	0	0
2007/2008	3	0	0
2008/2009	1	0	2
2009/2010	3	0	1
2010/2011	1	0	1
2011/2012	0	0	0
2012/2013	1	0	1
2013/2014	0	0	1
2014/2015	1	0	0
2015/2016	2	0	0
2016/2017	1	0	0
2017/2018	1	0	0
Totals	45	7	30

^a A foul-hooked white-chinned petrel *Procellaria aequinoctialis* was also recorded that season, but there is no systematic monitoring of this species and the record is not considered further.

nevertheless appears that this species and grey-headed albatrosses are rarely, if ever, caught alive. The at-sea distribution of light-mantled albatross currently overlaps little with fisheries (Mackley et al., 2010; Phillips et al., 2005a), but did so prior to the introduction in 1997 of a summer closed-season in the demersal fishery for Patagonian toothfish *Dissostichus eleginoides* around South Georgia. Similarly, grey-headed albatrosses formerly overlapped during breeding with the local toothfish fishery, and still overlap with various pelagic and demersal fisheries in the nonbreeding season when their distribution is circumpolar (Clay et al., 2019). Grey-headed albatrosses are killed during setting in some longline fisheries, but less often than other albatross and petrel species, suggesting they are generally out-competed behind vessels (Delord et al., 2005; Robertson et al., 2014; Ryan and Boix-Hinzen, 1999). This would also reduce their susceptibility to live capture during hauling.

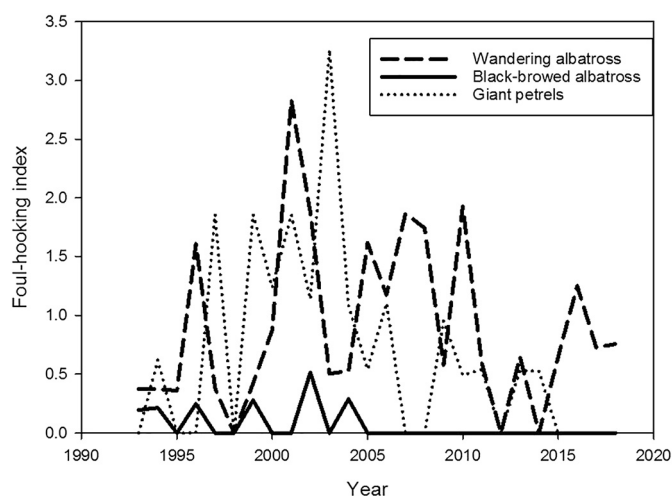


Fig. 2. Change in foul-hooking indices for wandering and black-browed albatrosses, and giant petrels seen entangled at Bird Island, South Georgia in austral summers 1992/93 to 2017/18.

By comparison, the at-sea ranges of wandering and black-browed albatrosses, and both giant petrel species overlap extensively with multiple fisheries, and they frequently interact with vessels (Clay et al., 2019; González-Solís et al., 2007). Although there are seasonal changes in distributions of birds and fishing effort, which affects bycatch rates (Weimerskirch et al., 2000), similar numbers of wandering albatrosses were reported as live-caught in each year-quarter. Birds, particularly juveniles, immatures and nonbreeding adults, are therefore susceptible to live-capture year-round (Table 1), related to their wide distributions and overlap with multiple fisheries (Clay et al., 2019; Thiers et al., 2014). Based on the ring reports, the vast majority of live-capture of seabirds from South Georgia is in pelagic or demersal longline fisheries, and is widespread, involving vessels from multiple flag states operating in the High Seas and on continental or island-shelf EEZs (Table 2, Fig. 1). The proportion of bycaught seabirds that are caught alive is generally higher in demersal than pelagic longline fisheries; 5–90% vs. 3–75%, or, if the two extreme values are excluded (Hawaiian pelagic and Chilean artisanal fisheries), 5–70% (mean 40.4%) vs. 3–23% (mean 10.7%) (Table 1). Factors such as the seabird species-assemblage and relative abundance contribute to the variation among regions, as do operational factors, e.g., live-capture rates are lower on Uruguayan and Brazilian pelagic longline vessels because they use shorter branch lines than Japanese and Taiwanese vessels (Gianuca and Jiménez, pers. comm.).

The low live-capture rates of black-browed albatrosses (both ring reports and colony-based observations) relative to other species in our study may also relate to regional differences in species assemblage. Since the summer closure of the local toothfish fishery, black-browed albatrosses from South Georgia overlap mainly with pelagic and demersal longliners off South Africa and Namibia in the nonbreeding season (Clay et al., 2019; Phillips et al., 2005b). Live-captures by demersal longliners off South Africa predominantly involve white-chinned petrels *Procellaria aequinoctialis*, great shearwaters *Ardenna gravis* and Cape gannets *Morus capensis* (Petersen et al., 2009). One possibility is therefore that these three species monopolise access to baits during hauling, reducing live captures of black-browed and other albatrosses in that region. This compares with the situation around the Falklands where these three species are rare or absent, and black-browed albatrosses, giant petrels and Cape petrels *Daption capense* are the most common live-caught species (Otley et al., 2007b).

Based on at-sea distributions, live-capture of wandering albatrosses and giant petrels from our study site is most likely in demersal fisheries around the Falklands, Argentina, Chile and South Georgia (Clay et al.,

2019; González-Solís et al., 2007; Granroth-Wilding and Phillips, 2019). Vessels off the Falklands and South Georgia attract hundreds of giant petrels, and although competition with better divers or more manoeuvrable species appears to reduce hooking risk during setting, giant petrels are particularly susceptible to live-capture during hauling (Otley et al., 2007a). The foul-hooking indices for wandering albatrosses and giant petrels at Bird Island increased from the mid-late 1990s to peaks in the early-mid 2000s, and then declined. This appears to reflect a genuine reduction in risk, although the timing is approximate as birds may not be seen at the colony for months or years after foul-hooking. Nevertheless it broadly mirrors general improvements in bird-bycatch mitigation at South Georgia and the Falklands from the late 1990s to early 2000s (Croxall and Nicol, 2004; Otley et al., 2007b; Varty et al., 2008). Wandering and black-browed albatrosses, and giant petrels were recorded as bycatch (dead) between 2001 and 2010 in Argentinian longline fisheries for toothfish and kingclip *Genypterus blacodes* (Favero et al., 2013). Given the six-fold decrease in effort in those fisheries over that period, and the order of magnitude reduction in bycatch, a similar decline in live-capture rate is likely. Finally, wandering and black-browed albatrosses from South Georgia may have been captured alive in Chilean toothfish fisheries, but introduction of a new fishing system in 2006 - hooks set in clusters and a net sleeve that drops over the catch during hauling - has virtually eliminated seabird bycatch during setting and hauling (Moreno et al., 2008; Robertson et al., 2014).

The broad temporal correspondence with changing fishing effort and practices suggests that records of foul-hooked birds at colonies can be a robust index of relative live-capture risk for different species over time and can be a useful adjunct to vessel-based monitoring in fisheries with low observer coverage or inadequate reporting of live captures. In theory, gear recovered from entangled birds might help identify fisheries for targeting efforts to improve regulation and monitoring. However, a previous attempt to determine source fleets of several hundred hooks and line collected around nests - albeit resulting from ingestion of discarded non-target catch rather than entanglements - found these were rarely diagnostic of a particular fleet (Phillips et al., 2010; Ridley et al., 2010). There are also issues of representativeness: embedded hooks in birds in infrequently-visited subcolonies are often corroded, and hence foul-hooking could have occurred many years before in a fishery that has since improved practices; hooks used in pelagic longlining are expensive and there is more incentive to recover them from live-caught birds, and; hooks lodged internally (indicated by trailing line out the bill) can rarely be recovered without causing major injury.

4.2. Survival rates of live-caught birds

Although live-capture of seabirds during hauling in longline fisheries was recognised as a major issue by the early 2000s (Table 1), as far as we are aware, ours is the first study to estimate post-release survival rates. This reflects the huge challenge of determining subsequent fate. Unless already ringed, live-caught birds lack information on provenance (except single-island endemics), and on sex and age class unless distinguishable from morphology. Although birds could be ringed or the plumage marked on board the vessel, these approaches do not allow survival rates to be fully quantified because unique marks visible from a distance would be necessary in order to follow the fates of individuals, and movements away from fishing areas or to nesting colonies without comprehensive monitoring would be indistinguishable from mortality.

Tracking devices would be effective for determining survival in weeks or months following release if they transmit to the ARGOS satellite system, via GSM if network coverage is available, or to a base station if the colony of origin is known. Disadvantages include: high cost of devices and ARGOS time (limiting sample sizes); availability of an on-board observer with experience of attaching devices on the infrequent occasions when birds are live-caught during routine fishing operations, and; loss of transmitters taped to feathers because the tape

degrades, feathers are moulted or are detached by the bird. Use of harnesses to try to extend deployment duration is not advisable because this results in very high mortality in pelagic seabirds (Phillips et al., 2003; Thaxter et al., 2016). An alternative is to use subcutaneous sutures to anchor devices in the skin (Hedd et al., 2018; Ronconi et al., 2018), but this may not be acceptable to some licensing authorities because of animal welfare considerations.

Analysis of ring reports is therefore a much lower-cost alternative but only under specific circumstances; a large sample of ringed birds of known provenance from a colony monitored with sufficient intensity that survivors are likely to be resighted. These conditions were satisfied in our study only for wandering albatrosses, as all nests with a ringed parent have been monitored, all chicks ringed each year since 1976, and emigration rates to other islands in the South Georgia group are negligible (Pardo et al., 2017). Although there is intensive monitoring of some subcolonies of the other albatross species, birds with a metal ring only that breed elsewhere on Bird Island will often be missed. The results for wandering albatross should be robust even in the absence of more complex multi-state capture-mark-recapture modelling (which would have estimation problems given the small sample of live-caught birds). Annual resighting rates of ringed birds breeding at the study site exceed 95% and hence any ringed adult caught in a fishery that returns to breed, or ringed chick that lives to recruitment is very unlikely to be missed as a breeder in more than one year.

Our results indicate that the survival rate of wandering albatrosses caught and released alive from longline fisheries was < 40% of that expected in the wider population. There are uncertainties associated with the small sample ($n = 19$), proportion of breeders missed each year (< 5%) and possible ring loss or emigration (albeit rare), but the conclusion that live-capture in a fishery has a substantial impact on survival probability is inescapable. On a more positive note, these data, and the number of birds with hooks or entangled in line that are seen at the colony, clearly indicate that wandering and black-browed albatrosses, and giant petrels, do survive capture in both pelagic and demersal longline fisheries. This should be encouraging for crew and fisheries observers that make efforts to release birds.

Based on the limited data available, Brothers (2016) estimated that at least 3500–7350 birds are caught and released alive each year in pelagic longline fisheries. There is no estimate for demersal fisheries, but as live-captures are proportionally more common (Table 1), and seabird bycatch is higher than in pelagic longline fisheries (Anderson et al., 2011), the total is likely to be much greater. A reduction in survival rate of live-caught birds by around 60% therefore has major implications for ecological risk assessments (ERAs) that seek to determine the impacts of fisheries (Small et al., 2013). This is particularly as most ERAs do not explicitly consider mortality associated with capture during hauling (Bakker et al., 2018; Tuck et al., 2011; Waugh et al., 2008; Waugh et al., 2012), and nor do most National Plans of Action for Seabirds (NPOA-Seabirds) (available at Cooper, 2018; but see Varty et al., 2008). The exception is the New Zealand risk assessment, which follows the precautionary principle; until recently, all birds released alive from fisheries were assumed to have died, but survival rate is now set at 50% (Richard et al., 2017). Most published studies of seabird bycatch do not discuss or quantify live-capture rates, sometimes because observers are not required to report these events. If the elevated mortality rate of live-caught wandering albatrosses is representative of other species, the estimate of at least 160,000 seabirds killed annually in global longline fisheries (Anderson et al., 2011) would need to be revised upwards by some considerable margin.

5. Conclusion and recommendations

Our results indicate that foul-hooking indices at colonies can provide an indication of relative risk for different seabird species over time, and be a useful adjunct to vessel-based monitoring of live-capture rates. Based on ring resighting, the subsequent survival rate of wandering

albatrosses live-caught and released was 40% of that expected for the wider population, although with the caveats associated with the small sample size for a species that, moreover, has a greater propensity than others to be caught during hauling. Regardless, our results lead to the following recommendations. (i) Ecological risk assessments of the impacts of fisheries bycatch on seabird populations should take into account the potentially much lower subsequent survival of live-caught birds, for example by including a cryptic mortality multiplier when scaling bycatch rates. (ii) Studies of survival of live-caught birds should be a high priority for research. (iii) A number of measures in theory deter birds from attacking longlines during hauling, including the Chilean net-sleeve system, water spray across the hauling area, strategic management of offal discharge (if not banned during hauling, then avoided on that side of the vessel), rapid retrieval (coiling) of branchlines, heavier weights closer to hooks, and a towed buoy, bird curtain or streamer (tori) line, designed to discourage birds from accessing the area of the baits (Gilman et al., 2014; Petersen et al., 2009; Pierre, 2018; Robertson et al., 2014). Confirmation of their effectiveness for reducing live captures and, if insufficient, development of new mitigation methods should be prioritised. (iv) As with other bycatch mitigation, fisheries regulatory authorities should mandate the use of best-practice approaches to avoid live-captures, ensure effective monitoring and impose punitive responses to deliberate non-compliance. (v) Existing bycatch observer programmes are often inadequate and the need for greater coverage, and improved data on the circumstances, species, age and sex of bycaught birds (Phillips, 2013), should be extended to include not just birds that die, but the condition of those captured alive and released. (vi) Observers need to be instructed that birds caught alive should be handled carefully, and if possible, efforts made to remove hooks with minimal trauma before release. There are published guidelines on hook removal, including those available from ACAP (<https://www.acap.aq/en/resources/acap-conservation-guidelines/2178-hook-removal-from-seabirds-guide-a3/file>).

CRedit author statement

Richard Phillips: Conceptualization, Methodology, Validation, Formal analysis, Writing – all stages, Supervision.

Andrew Wood: Data curation, Validation, Visualization, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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