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Significant reductions in mortality of threatened seabirds in a South African trawl fishery

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Abstract

Globally, many thousands of seabirds are killed accidentally in demersal trawl fisheries through cable interactions and net entanglements. However, multi-year datasets for estimating seabird–trawl interactions robustly are scarce. In 2004/2005, an estimated 15 500 (7000–26 000) seabirds were killed annually through cable strikes in the South African deep-water hake trawl fishery; the majority were albatrosses. We reanalysed those data using fishing effort from vessel logbooks (previously unavailable). The new estimates are ~40% lower across all taxa: ~9300 birds in 2004, of which ~7200 were albatrosses. We compare these figures to data from 2006 to 2010, when vessels used a single measure (bird-scaring lines) to reduce seabird mortality. From 64 trips and 690 hours of observation, 41 seabirds were confirmed killed due to cable strikes, of which 22% were albatrosses. Fatal cable interactions occurred overwhelmingly when vessels discarded offal, with the highest rates (birds killed per hour of observation) in winter and during setting. Comparing rates shows that bird-scaring lines alone resulted in 73–95% lower mortality in the winter/discard strata (all seabirds: 0.56 birds per hour before, 0.15 birds per hour after, $P < 0.001$; albatrosses: 0.44 birds per hour before, 0.02 birds per hour after, $P < 0.001$). Estimated total mortality [mean and 95% confidence intervals (CIs)] in this fishery in 2010 was 990 (556–1633) seabirds, including 83 (38–166) albatrosses, a reduction in mean albatross deaths of > 95%, reflecting both bird-scaring line effectiveness (accounting for > 90%) and annual fishing effort reduced by 50% from 2004–2005 to 2010. Bird-scaring lines cost < US$200 each in South Africa, a trivial expense per vessel for a measure that reduces fatal interactions with threatened seabirds so effectively. Our results provide a strong case for the mandatory adoption of bird-scaring lines in trawl fisheries with high densities of scavenging seabirds.

Introduction

Seabirds are amongst the most threatened group of birds in the world with pelagic species especially at risk (Croxall *et al*., 2012). Pelagic seabirds are unlike most other bird groups in that they cover huge distances when foraging and spend extended periods in international waters. Albatrosses and petrels in particular exhibit K-selected life history traits (Warham, 1996): they produce few offspring, have delayed sexual maturity and have high adult survival rates. As a consequence, population decreases can occur even with relatively modest increases in adult mortality rates (Croxall & Gales, 1998; Gales, 1998). A substantial body of literature has identified interactions with commercial fisheries as a major cause of declines in seabird populations (Brothers, Cooper & Løkkeborg, 1999; Ryan, Keith & Kroese, 2002; Sullivan & Reid, 2003; Baird, 2004; Petersen *et al*., 2008; Anderson *et al*., 2011; Løkkeborg, 2011; Tuck *et al*., 2011). Initially, longline fishing was identified as the main threat to seabirds (Brothers *et al*., 1999), but since then significant mortalities in demersal trawl fisheries have been documented (Bartle, 1991; Weimerskirch, Capdeville & Duhamel, 2000; Sullivan, Reid & Bugoni, 2006; Watkins, Petersen & Ryan, 2008; Abraham, 2010). During trawling operations seabirds are injured and accidentally killed primarily through collisions with trawl cables (also referred to as warps), net sonde cables and net entanglements (Bull, 2009).

The deep-water hake trawl fishery is the most commercially valuable fishery in South Africa (FAO, 2006). This fishery targets Cape hakes, *Merluccius paradoxus* (deep-water hake) and *M. capensis* (shallow-water hake). Since imposing total allowable catches (TACs) in 1978, annual catches have remained relatively stable in the 120 000–160 000 ton range (Powers *et al*., 2010).

The fishery consists of wet fish and freezer vessels. Wet fish vessels store processed fish (headed and gutted or just gutted) on ice and trips typically last 3–8 days. Freezer vessels conduct longer trips, typically 2–6 weeks (B. Rose, pers. comm.), mainly process fillets on-board into frozen, boxed products and produce fishmeal (and therefore produce minimal discards). In this paper we only consider the observed part of the fishery (daylight, wet fish trawl effort, not freezer vessels); this is the same portion of the fishery considered by Watkins *et al*. (2008).

In 2004, this fishery achieved Marine Stewardship Council (MSC) certification (Powers *et al*., 2004). Certification requires, *inter alia*, that the fishery must assess environmental (and especially by-catch species) impacts and work towards set standards of quantifying and reducing risks. During 2004 and 2005, the South African Deep Sea Trawl Industry Association (SADSTIA) investigated the nature and scale of potential seabird mortality associated with their fishing activities. Seabird interactions with trawl gear were observed and quantified, including through the use of video recording. Interaction rates (birds killed per hour of observation) were scaled up to crude estimates of total annual fishing effort, and mortality was estimated at 18 000 birds annually in this fishery, of which black-browed *Thalassarche melanophris* and shy-type albatrosses *T. cauta* (*sensu lato*) were most severely affected (Watkins *et al*., 2008). That study confirmed the strong influence of discarded fish/offal on seabird mortality rates, as in other demersal trawl fisheries (e.g. González-Zevallos & Yorio, 2006, Favero *et al*., 2011, Pierre *et al*., 2012), and recommended that, where discard management could not be implemented, alternative measures to reduce seabird by-catch be tested.

In 2006, BirdLife South Africa's Albatross Task Force (ATF) continued where the industry-funded programme left off, monitoring seabird by-catch in the trawl fishery. Bird-scaring lines (BSLs) were implemented in mid-2006 to keep birds away from the danger area around the cable in an effort to mitigate the high seabird mortalities (Watkins *et al*., 2008). In brief, BSLs consist of a ~30-m main line of strong rope, with 5–10 paired streamer lines of lighter, visible material, attached at 2-m intervals. The main line is secured to and deployed off the stern of the moving vessel, with a device at the seaward end of the main line (typically a road cone) providing drag that tensions the line and keeps it aloft behind the vessel, usually parallel with the trawl cables. The paired streamer lines hang downwards from the mainline and serve as a visual deterrent to seabirds (e.g. Sullivan *et al*., 2006, Petersen *et al*., 2008, Melvin *et al*., 2010). The compilation of data from 5 years of observations (2006–2010) provides an opportunity to compare current mortality rates with 2004–2005 rates, and to review the impacts of changed fishing practices, primarily the deployment of BSLs, on seabird mortality. We also re-estimate the 2004–2005 mortality using logbook data that were not previously available.

Materials and methods

Data collection

Data were collected by four ATF instructors between April 2006 and May 2011 on board 19 wet fish trawl vessels operated by four fishing companies. All vessels are required to keep accurate records of fishing activities, including location, water depth, times of various fishing activities, catch volumes by species and weather conditions in official logbooks. We used fishing effort data from these logbooks in our analyses. Furthermore, all observations since mid-2006 were made on vessels that had deployed two BSLs, and our observers ensured that the lines were in good repair and deployed correctly during observations.

On-deck protocols

Observers collected environmental data during daylight hours and recorded basic data (time, location and depth) for three fishing phases: setting (when gear is deployed), towing (when gear is dragged on the sea floor) and hauling (when gear is retrieved), collectively referred to as a trawl. During each phase, observers recorded fishery waste discard volumes (treated here as presence/absence) and seabird interactions with fishing gear, by species. Observations were made for the entire setting process (typically lasting 15–20 minutes). After setting ended, a bird count was conducted, and thereafter warp observations were resumed until ~10 minutes after discarding finished. Interactions were categorized according to Sullivan *et al*. (2006) as light and heavy, but only heavy interactions are analysed here. We classified two types of heavy interactions: surface, when birds contacted the trawl cable and were dragged under water, and aerial, when birds were visibly injured from striking the cable while in flight. The outcome following a heavy surface interaction was recorded as either uninjured, a mortality or uncertain. As bird carcasses are rarely hauled on-board in this fishery (cf. Sullivan *et al*., 2006), mortalities were recorded as any birds observed killed or birds failing to resurface after being dragged under water (and therefore presumed killed). Estimates given below are based on definite mortalities only (i.e. exclude uncertain outcomes), with the exception of birds that sustained serious injury (such as a broken wing) from aerial collisions with gear were recorded as mortalities, in keeping with other studies of seabird–trawl interactions (Sullivan *et al*., 2006; Watkins *et al*., 2008). These protocols are identical to those used in the previous study (Watkins *et al*., 2008), facilitating direct comparisons with their findings.

Analysis and comparison of interaction rates

The estimate of 15 500 birds killed per year from cable strikes in 2004–2005 (i.e. ignoring mortalities from net entanglements) was derived by extrapolating the calculated mortality rate (defined as the number of birds killed per unit of fishing effort) to the rest of the daytime, wet fish trawl fishery (Watkins *et al.*, 2008). However, they used heuristics to estimate effort (estimates of numbers of number of active vessels, daylight trawls per day, fishing days per vessel per year, etc.). We used the mortality rates from 2004 to 2005 but used official logbook effort data (unavailable to earlier authors) to revise the extrapolation to total annual mortality. Routine checks of logbook records by our observers and by independent fisheries observers suggest that logbooks are reliable for assessing total number of trawls per day (B. Maree, unpublished data).

A zero-inflated negative binomial generalized linear mixed model was developed and applied to the 2006–2010 data to assess the impacts of year, season, environmental and operational variables on interactions, but the model explained too little variance (< 15%). Consequently, we discarded a statistical modelling approach and no results from this are reported. Instead, an empirical, stratified approach was adopted whereby interaction rates were estimated separately for several strata of data and raised by fishing effort per stratum to estimate the total numbers of seabirds killed. Data were stratified by season and operational factors (phase of fishing and presence/absence of discards). Average interaction rates (birds per hour of observation) were calculated for the period 2006–2010 using a novel method, referred to as the proxy method. The proxy method takes advantage of the relationship between interaction rates and mortality rates, and has the effect of greatly increasing the numbers of bird–gear interaction events.

Watkins *et al.* (2008) found that presence/absence of discards, season (winter/summer) and fishing phase (set, tow or haul) had the strongest effects on seabird interaction rates. We stratified our data accordingly and combined all years to increase statistical power. As is typical of by-catch data, our observed mortality dataset is highly zero-inflated, with too few confirmed mortality events to estimate mortality rates in some strata with confidence. However, the heavy interactions dataset is much richer. In an analogous demersal trawl fishery in the Falkland Islands, which interacts with a similar suite of seabirds (dominated by large procellariiforms) the rates of heavy interactions and albatross mortality were positively correlated (Sullivan *et al.*, 2006). Based on this finding we assumed that any factors influencing mortality were likely to influence heavy interactions in the same way (i.e. any deviation from a linear relationship between heavy interactions and mortality is assumed to be random noise). We therefore used heavy interactions as a proxy for actual mortality in each step of the calculations. As the final step of analyses, the heavy interaction estimates were converted into mortality estimates using a conversion factor: the ratio of heavy interactions to deaths. Uncertainty about this conversion factor was treated by allowing for variation through bootstrap estimation of confidence intervals. Unless stated otherwise, the proxy method is adopted in the analysis of data below.

A full set of industry logbook data (observed and unobserved trawls) for 2006–2010 were used to scale up the results from observed trips to the fishery across 12 strata: summer/winter (winter being April to September, and summer being October to March), set/tow/haul and with/without discarding. Using the proxy method, 12 different mortality rates are estimated for each species group. To assign fishing effort to strata, we assumed that a discarding rate applies for the first hour of the trawl (including the setting phase), whereafter a non-discarding rate applies. This is based on an estimated 2 tons of catch processed per hour (B. Maree, unpublished data), which when applied to the average annual catch and average daylight fishing effort over the period yields a figure of ~1 hour of discarding per trawl. A non-discarding rate applies to the whole trawl if there is a break of more than 2 hours between end of hauling and start of next set (by which time all processing is normally completed and discarding ceases). As the bulk of discards exits from one side of a vessel, and observation effort was always directed to the side with most discards, an additional mortality rate equivalent to the non-discarding rate for the applicable season and fishing activity was applied to the second cable.

Assumptions and data limitations

No data were collected on-board freezer vessels (30–40% of total fishing effort during this study) or at night, and therefore estimates are for daylight trawls on wet fish vessels only, as for Watkins *et al.* (2008). As we recorded only one death from net entanglements, this minor mortality source is disregarded. Vessels may not always repair/replace damaged BSLs, deploy them or deploy them correctly when observers are not on-board. With no data to assess the likely scale of these assumptions, we have not accounted for them in this study, and readers should view the estimates of total annual seabird mortality with due caution. The placement of observers on-board in different seasons and over multiple years was assumed to provide an unbiased representation of the fishery, and as such no attempt was made to standardize with respect to environmental variables. However, the impacts arising from a potential bias in spatial coverage is explored in the supplementary information.

Annual total mortality in the fishery/extrapolation to the fleet level

In each stratum, h, and species group, G, the average number of heavy interactions per hour, r_h^G is scaled up by the amount of daytime fishery effort in that stratum and year E_y^h to obtain the total number of heavy interactions as an annual average between 2006 and 2010, H_G^F, calculated as follows:

$$H_G = \frac{\sum_{h}\sum_{y=2006}^{2010} r_h^G E_y^h}{5} \quad (1)$$

The average annual total mortality M_G in the fishery for species group G is estimated as the product of the annual number of heavy interactions and θ, the average number of deaths per heavy interaction:

$$M_G = H_G^F \, \theta \quad (2)$$

Some observer data from 2011 (seven trips) were included to improve statistical power for estimating seabird interaction parameters. However, fishing effort data were only available up to the end of 2010, and no references to results relating to fishing effort extend into 2011.

Confidence limits on the estimates of M_G were based on a bootstrap procedure. The bootstrap procedure was developed in Visual Basic and R, with very similar results. The bias-corrected and accelerated correction was applied in R, found to have negligible impact on the results and subsequently discarded. The Visual Basic bootstrap method used is as follows. Separate bootstraps were run for each species group (all birds and all albatrosses). The bootstrap used 1000 draws with replacement. For each draw i of the bootstrap, 57 trips were selected at random from the 57 observed trips between 2006 and 2010 (the entire dataset of 64 observed trips was used to estimate interaction rates but includes seven trips from 2011). The total number of heavy interactions was then calculated using the re-sampled trip information and the trawl effort information. For each iterate i, a value θ_i was drawn from a beta distribution β(41.5, 954.5), where 41 is the number of heavy interactions resulting in confirmed deaths for G = all birds, and 954 is the number of heavy interactions not resulting in death for G = all birds. The addition of 0.5 to both parameters is due to the use of the Jeffrey's prior β(0.5, 0.5). The combination of the data and the Jeffrey's prior yields the distribution upon which draws of θ_i are based. Note that θ_i as described here is the proportionality between the number of heavy interactions and the number of confirmed deaths for the i–th bootstrap iterate. We then calculated the total number of deaths by multiplying the number of heavy interactions by the proportionality coefficient (i.e. the number of confirmed deaths per heavy interaction). That is,

$$M_i^G = \theta_i \, H_i^G$$

The 95% confidence limits were the 2.5 and 97.5 percentiles from the 1000 bootstrap results.

Comparison with historical estimate

Watkins *et al*. (2008) estimated mortality rates (birds per hour) using confirmed mortalities rather than the proxy method (which uses heavy interactions and their relationship to mortality). Thus direct, statistically valid comparisons of results between studies are not possible. To facilitate tests of significance in differences in interaction rates between the periods, we used our newer dataset and calculated mortality rates from direct mortalities – the same methodological approach used in the earlier study. Mortality was estimated across four strata: summer/winter and with/without discards. Rates from the two study periods were compared using *t*-tests for two species groups (all birds and all albatross). However, this was done exclusively for testing rates differences between study periods and all other results presented here are based on the proxy method.

Results

Summary observer and fishery effort data

In total, 64 trips and 782 trawls were observed, amounting to 0.3–1.3% of annual wet fish effort (Table 1). However, because observer data from different years were combined, when raising estimated rates to annual fishing effort the effective observer coverage was ~4% of annual effort. There were 996 heavy interactions and 41 mortalities in 690 hours of observation (Table 2). Individuals of five species of conservation concern were killed by this fishery, constituting 41% (17 of 41) of all mortalities observed, but numerically the pintado petrel *Daption capense* dominated both heavy interactions and confirmed mortalities (Table 2). Only two non-procellariiform seabirds (Cape gannet *Morus capensis* and subantarctic skua *Catharacta antarctica*) were recorded interacting with cables.

Table 1 All fishing effort, wet fish vessels' effort and observer effort (number of observed trips, trawls and observation duration) in the South African deep-water hake trawl fishery, 2006–2011

Year	All trawls	Wet fish trawls	Observed trips	Observed trawls	Observation hours	Observed wet fish effort (%)
2006	34 403	21 556	4	58	77.9	0.3
2007	32 237	20 572	6	69	62.6	0.3
2008	26 323	17 892	7	93	75.1	0.5
2009	29 584	22 925	17	237	228.9	1.0
2010	27 232	19 714	23	260	190.9	1.3
2011	–	–	7	65	55.5	–

Interaction rates

Proxy method

The ratio of confirmed deaths to heavy interactions for all birds in the study was 0.04 (41 deaths out of 996 heavy interactions, Table 2). Thus the rate r_h^G (heavy interactions per hour) in each stratum was converted to mortality at the final stage of calculation at a conversion rate of 0.04 deaths per heavy interaction.

For both species groups, mortality rates calculated across 12 strata were highest when discarding occurred, and were higher in winter than in summer. There were large differences in mortality rates between fishing phases, being highest during the setting phase and lowest during the hauling phase (Table 3).

Comparison with historical estimate

In both periods (2004–2005 and 2006–2010), cable strike rates were zero or virtually zero across all strata when no discarding occurred, and there were no significant effects over time within non-discarding strata for either species group (Table 4). However, when discarding occurred, there were significant reductions in interaction rates between study periods for both seasons and both species groups; all *t*-tests were highly significant ($P < 0.001$, Table 4). The mortality rate estimates in discard strata for albatrosses decreased in summer from 0.17 birds per hour before BSLs to 0.03 birds per hour after BSLs (83% decrease). The effect of BSLs was even stronger in winter, decreasing from 0.44 birds per hour before BSLs to 0.02 birds per hour after BSLs were introduced, a reduction of 95% in the mortality rate.

Table 2 Total observed heavy interactions and mortalities observed, by species, in the South African deep-water hake trawl wet fish fishery, 2006–2010, ranked by International Union for Conservation of Nature (IUCN) conservation status and numbers observed killed

Species	Status[a]	Heavy interactions	Observed mortalities	Ratio[b]
Black-browed albatross *Thalassarche melanophris*	EN	60	6	10.0
Indian yellow-nosed albatross *T. carteri*	EN	7	1	14.3
Atlantic yellow-nosed albatross *T. chlororhynchos*	EN	2	0	–
White-chinned petrel *Procellaria aequinoctialis*	VU	124	3	2.4
Cape gannet *Morus capensis*	VU	110	5	4.5
Shy-type albatross *T. cauta*	NT	30	2	6.7
Pintado petrel *Daption capense*	LC	612	21	3.4
Great shearwater *Puffinus gravis*	LC	27	1	3.7
Subantarctic skua *Catharacta antarctica*	LC	12	1	8.3
Sooty shearwater *Puffinus griseus*	LC	2	1	50.0
Giant petrel spp. *Macronectes* spp.	LC	7	0	–
Albatross spp. *Thalassarche* spp.	–	3	0	–
Total		996	41	4.1

[a]IUCN conservation status in 2012: EN, endangered; VU, vulnerable; NT, near threatened; LC, least concern.
[b]Ratio = heavy interactions/mortality.

Table 3 Heavy interaction rates and mortality rates (birds per hour) for daylight trawls estimated using the proxy method across 12 strata. Data for the South African deep-water hake trawl wet fish fishery

Season and discard status	Phase	Heavy interaction rates: All albatross	Heavy interaction rates: All birds	Mortality rates: All albatross	Mortality rates: All birds
S + D	Set	0.57 (0.54)	1.57 (0.94)	0.02 (0.02)	0.07 (0.04)
W + D	Set	0.63 (0.45)	3.73 (0.81)	0.03 (0.03)	0.16 (0.07)
S + D	Tow	0.13 (0.10)	0.85 (0.41)	0.005 (0.005)	0.04 (0.03)
W + D	Tow	0.05 (0.03)	4.17 (1.34)	0.002 (0.002)	0.17 (0.08)
S + D	Haul	0	0	0	0
W + D	Haul	0	0.10 (0.10)	0	0.004 (0.004)
S + ND	Set	0.19 (0.17)	0.53 (0.41)	0.008 (0.008)	0.02 (0.01)
W + ND	Set	0.07 (0.03)	0.22 (0.16)	0.003 (0.003)	0.01 (0.006)
S + ND	Tow	0	0.02 (0.02)	0	0.001 (0.0006)
W + ND	Tow	0	0	0	0
S + ND	Haul	0	0	0	0
W + ND	Haul	0	0	0	0

Standard error (SE) in parentheses.
S, summer; W, winter; D, with discards; ND, no discards.

Table 4 Mortality rates (birds per hour) in the South African deep-water hake trawl wet fish fishery for daylight trawls, estimated using only observed mortalities, for comparison between 2004–2005 and 2006–2010

Species group	Stratum	2004–2005	2006–2010*	T	*P*	d.f.
All albatross	S + D	0.17	0.03 (0.011)	13.217	< 0.001	693
	W + D	0.44	0.02 (0.008)	49.572	< 0.001	859
	S + ND	0.0	0.0			
	W + ND	0.07	0.0			
All birds	S + D	0.21	0.05 (0.010)	15.891	< 0.001	693
	W + D	0.56	0.15 (0.023)	17.815	< 0.001	859
	S + ND	0.0	0.0			
	W + ND	0.09	0.0			

*These values were not used to estimate total annual mortalities and differ from estimates derived using the proxy method (Table 3).
Standard error (SE) in parentheses.
S, summer; W, winter; D, with discards; ND, no discards.

The reductions in mortality rates in the discard strata for all birds was less (73–76% in the two seasons), but still significant (Table 4).

Annual total mortality in the fishery

Revision of earlier mortality estimate

The previous estimates of total annual seabird mortalities in the relevant portion of this fishery were based on a crude estimate of 35 000 hours of high-risk effort (daylight trawls with discards) annually. Logbook data on effort revealed this was a substantial overestimate (~40%). As a consequence, total annual mortality in the 2004–2005 period was likely to have been ~9300 seabirds per year, of which ~7200 were albatrosses.

Although mortality rates are best for direct comparisons over time (Table 3) or across strata or even other fisheries, it is necessary to estimate total annual mortality so as to account for inter-annual differences in fishing effort. Annual reductions in fishing effort resulted in total mortalities that were > 55% lower in 2010 than in 2006 (Table 5). Although we revised downward the estimates of total annual mortality in 2004–2005, the reductions in numbers of birds killed are nonetheless impressive. For all seabirds there was a 90% reduction, from 9300 seabirds in 2004–2005 to 990 in 2010 (Table 5). The fate of albatrosses interacting with this fishery improved still more dramatically, from an estimated ~7200 annual deaths in 2004–2005 to < 100 annual deaths since 2009 (Table 5), a decrease of ~99%.

Some fisheries report seabird interactions as numbers of birds killed per trawl day per vessel or birds per trawl rather than per hour of observation. In this fishery, each vessel sets on average four times a day, so seabirds are at risk for ~4 hours per trawl day per vessel. The rates reported here are equivalent to 0.04 albatrosses per trawl day per vessel and 0.64 birds per trawl day per vessel.

Table 5 Estimates of total annual mortality for all albatross and all birds in the South African deep-water hake trawl wet fish fishery (using the proxy method). Estimates are derived from combining all years' seabird interaction data to estimate rates, and applying those to annual fishing effort

Year	Fishing effort (daylight hours)	All albatross[a]	All birds[a]
2004	71 314	~7200 (3300–12 600)[b]	9300 (4800–18 600)[b]
2005	73 137		
2006[c]	66 530	193 (88–387)	2264 (1273–3735)
2007	60 160	176 (81–353)	2046 (1150–3376)
2008	51 033	144 (66–289)	1679 (944–2770)
2009	35 449	99 (45–198)	1141 (641–1883)
2010	29 896	83 (38–166)	990 (556–1633)

[a]Approximate 95% confidence interval (CI) given in parentheses, determined by rescaling the interval from all years combined, in proportion to annual effort.
[b]Based on values published by Watkins *et al.* (2008), rescaled to account for lower fishing effort.
[c]Bird-scaring lines (BSLs) were made mandatory in mid-2006 and compliance improved over time; consequently, actual mortalities in 2006 are likely to be higher in this estimate, which uses a multi-year rate where BSLs were in use.

Discussion

This study confirms the overwhelming impact that discarding has on seabird interactions with trawl vessels (Watkins *et al.*, 2008; see also González-Zevallos & Yorio, 2006, Favero *et al.*, 2011, Pierre *et al.*, 2012). The key novel result relates to the deployment of a measure from 2006 onwards to mitigate impacts on seabirds – specifically the impact of BSLs. This is the only operational variable that changed since seabird mortality rates in the South African deep-water hake trawl fishery were first estimated, and we conclude that it is responsible for the 73–95% reduction in mortality rates compared with 2004–2005. This suggests a degree of effectiveness of BSLs for albatrosses similar to that reported from the Falkland Islands (Sullivan *et al.*, 2006) and for seabird strikes documented in the eastern Bering Sea (Melvin *et al.*, 2010). When these rates are scaled up to total fishing effort to estimate total annual mortalities, the decreases over time are even more striking because they combine with a halving of fishing effort during the study. Despite the 2010 estimated mortality being benchmarked against revised totals from the 2004–2005 period that are

~40% lower than originally estimated, mean annual albatross mortality has been reduced > 95%, to negligible levels. A significant gap in this study is potential seabird mortality from freezer vessels, currently 30–40% of total fishing effort; this requires further investigation. However, if BSLs are routinely deployed in accordance with fishing permit conditions, this sector of the fishery will not add large numbers to the total mortality estimates.

By-catch rates and the extrapolated estimates of fishery-wide mortality provide useful but different insights into levels of seabird mortality. Rates require fewer assumptions and are best for comparing trends over time, as long as the methods used by observers are consistent, as in this case. However, use of by-catch rates alone as a performance measure for by-catch reduction is insufficient to achieve conservation goals. Lower rates could arise from a collapsing seabird population, for example Tuck (2011). That possibility is unlikely to have influenced the results in this study because the population numbers of the species most at risk are decreasing too slowly (e.g. Poncet *et al*., 2006; ACAP, 2009; Croxall *et al*., 2012). Equally, total mortality is correlated with levels of fishing effort. Self-evidently, a constant mortality rate will result in variable total impacts as effort changes; in this case, a halving of fishing effort from 2004 to 2010 contributed to the lower annual mortality total for 2010.

Although a reduction of 90% in total annual mortality of all seabird species is reported, this is largely driven by the albatross figures, and in reality there has been a shift in risk from large birds (albatrosses) to smaller species. This is particularly noticeable for pintado petrels, which were not recorded as being killed in 2004–2005 (Watkins *et al*., 2008) whereas they constituted half (21 of 41, Table 2) of the observed mortalities in this study. This may reflect the fact that BSLs are effective at keeping albatrosses out of the danger area, which removes foraging competition in the direct vicinity of the trawl cables. This result should be viewed in context of conservation risks. Seventeen of the 41 fatalities (41%), belong to five species of conservation concern (BirdLife International, 2012). When scaled up, this equates to ~400 individuals of threatened species killed per year. While it is gratifying to note that the albatrosses (of highest conservation concern) are at substantially reduced risk, concerns remain for other vulnerable species observed to be killed, including white-chinned petrels *Procellaria aequinoctialis* ($n = 3$) and Cape gannets ($n = 5$), both listed as vulnerable (BirdLife International, 2012). The mortality rates for nocturnally active white-chinned petrels may be substantially underestimated because we have no observations of nocturnal interactions (which requires dedicated research with night-vision or infrared equipment). Cape gannet mortality remains difficult to mitigate due to their plunge-diving behaviour, which renders BSLs less effective against them than against procellariiforms (B. Maree, pers. obs.).

There are two principal reasons why the setting phase had the highest by-catch rates. First, this fishery is governed by regulations issued with fishing permits, and from mid-2006 deployment of BSLs was mandatory. However, the conditions only required that BSLs were deployed after setting. Further, although permit conditions included strictures against discarding during setting, few vessels complied (ATF, unpublished data). Thus cables remained exposed during this phase, which is also typically a period of intense seabird activity (B. Maree, pers. obs.). Second, during setting, cables are moving downwards as the net sinks. This exacerbates the downward force of the water against the cables and serves to drag entangled birds down with greater effect. The elevated mortality rate during setting was initially addressed in 2011, through a voluntary decision from the industry body (SADSTIA) to deploy BSLs during the setting phase (R. Bross, in litt.) and more recently through changes to conditions in the 2012 fishing permits.

The implications of this study extend beyond the encouraging results for the species interacting with trawl gear in South Africa. Data on rare events such as by-catch of seabirds are not only difficult to obtain, but are notoriously difficult to analyse and extrapolate from (Ashford, 2002; Lawson, 2006; Pradhan & Leung, 2006; Sims, Cox & Lewison, 2008). Two statistical approaches adopted here enabled robust analysis, which overcomes to some extent the low levels of annual observer coverage. First was a conventional approach, which assumed no annual effects and allowed lumping of all years of observer data; this greatly increased the effective sample size (and thus reduced confidence intervals around the estimates) when applying estimated rates to total fishing effort in each year. This clearly demonstrates the value of large datasets, in this case spread across multiple years. Second was the proxy method, which took advantage of the relationship between heavy interactions and mortalities first identified by Sullivan *et al*. (2006). In our study, heavy interactions were an order of magnitude more common than mortalities, and they scaled consistently across taxa. Thus the proxy method incorporated a much richer dataset of seabird–cable interactions than the direct method; this again reduced the confidence intervals around our estimates. Studies of fisheries by-catch and other rare events should seek similar proxies (such as relationships between abundance and risk of capture).

Watkins *et al*. (2008) estimated confidence intervals using a bootstrap procedure and individual observations of seabirds as the sampling unit (P. Ryan, in litt). That approach does not address the likelihood of non-independence of within-trawl or within-trip observations. To overcome those concerns, the bootstrap procedure used in this study was based on trip as the sampling unit. However, the method in this study also differs from the Watkins *et al*. (2008) method because it uses the number of heavy interactions (as an intermediate variable) instead of the much more depauperate (and hence more variable) dataset of observed mortalities only. The use of trip rather than observation as a sampling unit is expected to inflate the standard error of seabird mortality estimates, while the use of the heavy interactions is likely to deflate it.

In a global context, the risk to seabirds from trawl fishing is poorly understood, but impacts have been found in North and South Atlantic, North and South Pacific and South Indian oceans (Pierce *et al.*, 2002; Watkins *et al.*, 2008; Melvin *et al.*, 2010; Favero *et al.*, 2011; Pierre *et al.*, 2012). The entire, annual catch of hake in South Africa's deep-water trawl fishery is 130 000–150 000 tonnes, < 1% of the annual global catch from demersal finfish trawls (16–20 million tonnes, FAO, 2005, 2012), which accounts for ~40% of annual global fish catches (Watson, Revenga & Kura, 2006). Due to their global distribution and scale, as well as the extent of seabird interactions, trawl fisheries have been highlighted as a source of conservation concern (Croxall, 2008). Retrofitting vessels to eliminate, reduce or otherwise manage discards for the benefit of reducing risks to seabirds is extremely expensive, and in South Africa the industry has baulked at those costs. Fortunately, BSLs are cheap to build, simple to deploy, and our results confirm that when used appropriately they are very effective at reducing significantly seabird mortality from cable interactions (Sullivan *et al.*, 2006; Bull, 2009; Abraham, 2010). A BSL built to best-practice specification (ACAP, 2011) costs < US$100 to construct in South Africa, a trivial expense for each vessel to incur for a measure that reduces fatal interactions with threatened seabirds significantly. All trawl fisheries across the globe should assess potential seabird interactions, especially fisheries operating in regions with high abundances of mid- and large-sized procellariiform seabirds (Watkins *et al.*, 2008; Pierre *et al.*, 2012). Where mortalities occur, vessels should deploy BSLs built according to published best practice design specifications (Melvin *et al.*, 2010; ACAP, 2011).

When no discarding occurs, seabird–cable collisions are almost non-existent (Sullivan *et al.*, 2006; Watkins *et al.*, 2008; Pierre *et al.*, 2012; this study). Thus elimination of seabird mortality in this and other trawl fisheries can be achieved through eliminating discards when cables are in the water and seabirds are foraging (Wienecke & Robertson, 2002, Watkins *et al.*, 2008; Abraham *et al.*, 2009; Bull, 2009; ACAP, 2011; Favero *et al.*, 2011). Options for vessels to manage discard regimes include discarding retention ponds, fishmeal plants and discarding through the hull (Abraham *et al.*, 2009; Melvin *et al.*, 2010; Pierre *et al.*, 2012). Although retrofitting vessels for discard management may be prohibitively expensive, we suggest that all new vessels entering trawl fisheries comply with strict standards that prevent seabirds from accessing discards near the cable–water interface, including prohibitions on discarding while fishing gear is in the water.

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Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix S1. Spatial representivity.

Table S1. Estimates of bias arising from spatial non-representivity, between observed bird counts and expected values, for the South African deep-water hake trawl wet fish fishery for daylight trawls for the period 2006–2010.