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Contributed Paper

Lessons from seabird conservation in Alaskan longline fisheries

Edward F. Melvin [1], Kimberly S. Dietrich,[2] Robert M. Suryan [3]* and Shannon M. Fitzgerald[4]

[1]Washington Sea Grant, University of Washington, 3716 Brooklyn Avenue NE, Seattle, WA 98105, U.S.A., email edmelvin@uw.edu
[2]5091 Starfish Drive SE, St. Petersburg, FL 33705, U.S.A.
[3]Department of Fisheries and Wildlife, Oregon State University, Hatfield Marine Science Center, 2030 SE Marine Science Drive, Newport, OR 97365, U.S.A.
[4]Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way NE, Seattle, WA 98115, U.S.A.

Abstract: *Although bycatch of seabirds and other long-lived species is a critical conservation issue in world fisheries, case studies documenting significant reductions in the mortality of these low-productivity species in a fishery are rare. We studied progress toward seabird conservation in the Alaskan longline fisheries, one of the largest and most diverse demersal fisheries. We generated annual seabird bycatch rates in 4 target fisheries and all fisheries combined from 23 years of fisheries observer data. We used 0-inflated negative binomial models to evaluate variables influencing seabird bycatch per unit effort (BPUE) in 2 target fisheries. Following adoption of streamer lines, at first voluntarily and then mandatorily, seabird BPUE was reduced by 77–90%, preventing mortality of thousands of birds per year. Despite this, BPUE increased significantly in 2 of 4 target fisheries since streamer lines were adopted. Although night setting yielded significant reductions (74–97%) in seabird BPUE and significant increases (7–11%) in fish catch per unit effort over daytime setting, nighttime setting increased the BPUE of Northern Fulmar (*Fulmarus glacialis*) by 40% and nontarget fish species by 5–17%. Thus, best practices to prevent seabird mortalities in longline fisheries varied by species assemblage and fishery. Our results inform global efforts toward fisheries bycatch reduction by illustrating that successful conservation requires fishery-specific solutions, strong industry support, constant vigilance in analysis and reporting observer data, and ongoing outreach to fleets, especially to vessels with anomalously high BPUE.*

Keywords: best practice mitigation, bird scaring lines, case history, demersal longline fisheries, fishery specific solutions, night setting, seabird bycatch

Aprendizajes de la Conservación de Aves Marinas en las Pesquerías con Palangre de Alaska Melvin

Resumen: *Aunque la captura accesoria de aves marinas y otras especies con ciclos de vida largos es un asunto de importancia para la conservación en las pesquerías a nivel global, son raros los estudios de caso que documentan las reducciones significativas de la mortalidad de estas especies de baja productividad en las pesquerías. Estudiamos el progreso hacia la conservación de aves marinas en las pesquerías con palangre en Alaska, una de las pesquerías demersales más grandes y con mayor diversidad. Generamos tasas anuales de capturas accesorias de aves marinas para cuatro pesquerías y todas las pesquerías combinadas a partir de 23 años de datos de observación de pesquerías. Usamos modelos binomiales negativos con inflación 0 para evaluar las variables que influyen sobre la captura accesoria de aves marinas por unidad de esfuerzo (BPUE, en inglés) en dos pesquerías. Después de la adopción de la caña de pescar, al principio voluntariamente*

*Current address: NOAA Fisheries, Alaska Fisheries Science Center, Auke Bay Laboratories, Ted Steven's Marine Research Institute, 17109 Pt. Lena Loop Road, Juneau, AK 99801, U.S.A.
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y después de manera obligatoria, el BPUE de aves marinas se redujo entre un 77 y 90%, lo que previno la mortalidad de miles de aves por año. A pesar de esto, el BPUE incrementó significativamente en dos de las cuatro pesquerías diana desde que se adoptaron las cañas de pescar. Aunque las puestas nocturnas resultaron en reducciones significativas (74-97%) en el BPUE de aves marinas e incrementos significativos (7-11%) en la captura de peces por unidad de esfuerzo comparadas con las puestas diurnas, las puestas nocturnas incrementaron el BPUE del fulmar boreal (Fulmarus glacialis) en un 40% y entre un 5 y 17% el de las especies de peces cuya captura no es relevante para las pesquerías. Por lo tanto, las mejores prácticas para prevenir la mortalidad de las aves marinas en las pesquerías con palangre variaron dependiendo del grupo de especies y de la pesquería. Nuestros resultados informan a los esfuerzos globales hacia la reducción de la captura accesoria de las pesquerías al ilustrar que la conservación exitosa requiere de soluciones específicas por pesquería, un fuerte apoyo por parte de la industria, una vigilancia constante del análisis y el reporte de los datos de observación, y una participación continua de las flotas, especialmente en el caso de navíos con un BPUE anormalmente alto.

Palabras Clave: captura accesoria de aves marinas, historia de caso, líneas espanta aves, mitigación de mejor práctica, pesquerías demersales con palangre, puesta nocturna, soluciones específicas por pesquería

摘要: *尽管全世界的渔场都面临着海鸟和其它寿命长的物种遭到兼捕这样一个重要保护问题, 但关于渔场中这些低繁殖率物种的死亡率显著下降的案例分析仍然很少。本研究分析了规模最大、种类最多的底层渔场之一的阿拉斯加延绳钓渔场在海鸟保护方面的进展。我们根据 23 年间渔场的观察数据, 获得了四个目标渔场和所有渔场整体上每年海鸟兼捕率的数据, 并用零膨胀负二项模型估计了两个目标渔场中影响每单位工作量的海鸟兼捕量 (bycatch per unit effort, BPUE) 的因素。在从自愿到强制性地采用了飞绳钓方法之后, 海鸟 BPUE 减少了77-90%, 每年防止了数千只鸟的死亡。尽管如此, 采用飞绳钓后, 四个目标渔场中还是有两个渔场 BPUE 显著增加。虽然夜间放钓竿相比于日间放钓竿, 海鸟 BPUE 显著减少 (74-97%), 且每单位工作量的渔获量显著增加 (7-11%), 但夜间放钓竿导致暴雪鹱 (*Fulmarus glacialis*) 的 BPUE 增加了40%, 非目标鱼种的 BPUE 也增加了5-17%。因此, 防止延绳钓渔场中海鸟死亡的最佳实践取决于物种群落和渔场的具体情况。我们的结果阐明了成功的保护需要针对各个渔场制定解决方案、有强有力的产业支持、对观察数据的分析和报告保持谨慎, 以及要注意不断扩大的船队, 特别是引起异常高 BPUE 的船只。这些结果为全球渔场减少兼捕的努力提供了重要信息。***【翻译: 胡怡思; 审校: 聂永刚】**

关键词: 海鸟兼捕, 底层延绳钓渔场, 鸟类警戒线, 夜间布设钓竿, 减缓影响的最佳实践, 历史案例, 渔场特异的解决方案

Introduction

Incidental mortality (bycatch) of long-lived, low-productivity fauna (e.g., marine mammals, turtles, seabirds, elasmobranchs) ranks among the most critical conservation issues in world fisheries (Zydelis et al. 2009; Lewison et al. 2014). Stemming fishery bycatch, especially of the most vulnerable species, is a fundamental component of successful ecosystem-based fishery management (Hilborn 2011). Seabird bycatch in longline fisheries is linked to population declines and poor recovery of seabird populations and is the primary at-sea threat to albatrosses and petrels (Croxall et al. 2012). Attracted to offal and bait from fishing vessels, seabirds can become hooked and drown while foraging on baited hooks as they sink during longline deployment. The annual mortality of seabirds attributable to longline fisheries is estimated in the hundreds of thousands (Anderson et al. 2011).

Quantifying the extent of longline mortality relies on documentation by fishery observers and reporting by fishery managers. In general, the existence, extent, and quality of fishery observer programs and bycatch reporting vary across fisheries. Despite global attention in response to fishery-caused population declines and the development of best practice seabird-mitigation recommendations (CCAMLR 2003; ACAP 2010), few case studies exist documenting significant reductions in the mortality of seabirds or other low-productivity species in a fishery following the implementation of conservation measures (Cox et al. 2007).

In Alaska, from 1993 to 1999, estimated annual seabird bycatch of all seabird species averaged 16,137 birds/year (0.083 birds/1,000 hooks) and ranged from 9,171 to 26,270 birds (Fitzgerald et al. 2008). Seabird bycatch concerns in Alaskan longline fisheries initially focused on Short-tailed Albatross (*Phoebastria albatrus*), a species once thought extinct and now listed as vulnerable to extinction by global criteria (IUCN 2017) and endangered under the U.S. Endangered Species Act (ESA) (USFWS 2008). Regulation under the ESA established an incidental-take limit for Short-tailed Albatross from 1 bird annually to 6 birds biennially for all Alaskan longline fisheries. Conservation efforts also called for research to determine the effectiveness of recommended seabird deterrent measures, analyze options to improve their effectiveness, and modify existing regulations based on the outcome. In 1999 and 2000, the fishing industry, researchers, and fishery and wildlife managers collaborated on testing of seabird bycatch avoidance options in Alaskan longline fisheries. Streamer lines (or bird scaring or tori lines) were determined the best option because they reduced seabird bycatch per unit effort (BPUE) of surface-foraging birds, a guild that includes albatrosses, by 88–100% compared with no deterrent in the 2 fisheries examined (Melvin et al. 2001). Streamer lines with performance and material standards were adopted voluntarily by the fishing industry in 2002 and mandated in 2004.

We compared seabird BPUE in Alaskan longline fisheries based on 23 years of data collected by fisheries observers in the North Pacific Observer Program before and after the adoption of streamer lines and modeled recent trends in seabird BPUE in the sablefish (*Anoplopoma fimbria*) and Pacific cod (*Gadus macrocephalus*) fisheries following the adoption of streamer lines. We sought to determine whether seabird conservation can be achieved in a diverse demersal longline fishery with measures demonstrated to be effective through research; assess recent trends and evaluate variables influencing BPUE; and identify alternative management options that might further improve seabird conservation in Alaskan longline fisheries.

Methods

Fishery Description and Observer Data

The Alaskan longline fishery is one of the largest (US$300 million ex-vessel value) and most diverse demersal longline fisheries in the world. Mostly separate fleets target 4 species: sablefish, 300 vessels; Pacific halibut (*Hippoglossus stenolepis*), 900 vessels; Pacific cod, 130 vessels; and Greenland turbot (*Reinhardtius hippoglossoides*), 7 vessels.

Most fishing vessels operating in Alaska must have a fisheries observer for some or all of their fishing days. Prior to 2013, observer requirements were based on vessel length (minimum 38.1 m) and excluded the halibut fishery. With the restructuring of the observer program in 2013, vessel selection was randomized and observer coverage was expanded to include smaller vessels (minimum 12.2 m) and those targeting halibut. Target species is determined by the dominant species by weight landed following a given vessel trip and is not a factor in assigning observers to vessels (Cahalan et al. 2014).

Data Analyses

We analyzed observer program catch and effort data for Alaskan longline fisheries from 1993, when seabirds were first included in observer catch sampling, through 2015. We excluded sets with $<20\%$ of the hooks monitored, research sets, and sets with missing data (or $\sim2.5\%$ of the sampled sets).

Numbers of sampled hooks in a given set varied by more than 2 orders of magnitude; therefore, we used weighted means and standard errors of BPUE with sampled hooks as the weighting factor. We calculated SE of weighted means with the approximate ratio variance (Cochran 1977; Gatz & Smith 1995). We compared day versus night BPUE (birds/1,000 hooks) and target fish catch per unit effort (CPUE) (kg/1,000 hooks) after streamer-line adoption (2002 to 2015) with a nonparametric rank Mann–Whitney *U* test. In night sets, the first hook was deployed after civil dusk and before civil dawn (sun angle $>6°$ below horizon). We also examined the BPUE of individual vessels in the period following the restructuring of the observer program (2013 to 2015) to determine whether some vessels accounted for a disproportionate bycatch of seabirds.

Seabird bycatch events were rare and yielded data that were zero-inflated and overdispersed. We used a Vuong test to establish that zero-models were superior to noninflated models and a boundary likelihood ratio test to establish that a negative binomial distribution was preferred over a Poisson distribution in zero-inflated models (Hilbe 2013). Zero-inflated negative binomial models that incorporate a count and binomial processes in the same model (Hilbe 2013; Zuur & Ieno 2016*a*, 2016*b*) were used to evaluate variables influencing seabird BPUE (Supporting Information). The response variable was the number of birds caught in a sample (within a set); the log of sampled hooks was included as an offset. We used a forward, followed by a backward, stepping variable-selection process that retained variables with the lowest AIC and were significant based on standard likelihood-ratio tests (Hilbe 2013). We also monitored changes to the dispersion statistic and the significance of robust SE estimates around coefficients. We excluded models with large SEs around coefficients even if AIC improved. Final models were those with the fewest factors relative to competing models within a ΔAIC of <2 (Burnham & Anderson 2002). The full time-series models included 3 terms (Supporting Information), and all single-term interactions were tested. Postadoption models included nearly 3 times as many terms (Supporting Information); therefore, we included only a subset of possible single-term interactions based on relevance to our objectives, potential fisheries management implications, and results from previous studies (Dietrich et al. 2009). All analyses were conducted in R statistical software version 3.3.2 with the pscl and lmtest packages (Zeileis et al. 2008; Jackman 2015; R Core Team 2016).

For our models and most comparisons, seabirds were categorized as albatross (Laysan [*Phoebastria immutabilis*], Black-footed [*P. nigripes*], Short-tailed [*P. albatrus*]) or nonalbatross (primarily Northern Fulmar [*Fulmarus glacialis*], gulls [*Larus* spp.], and shearwaters, Short-tailed [*Ardenna tenuirostris*] and Sooty [*A. grisea*]). We modeled BPUE with respect to all or a subset of 4 temporal (pre- or poststreamer-lines era, year, season, time of day), 2 spatial (area, water depth), and 3 fishery (processor type, hooks set, target CPUE) variables

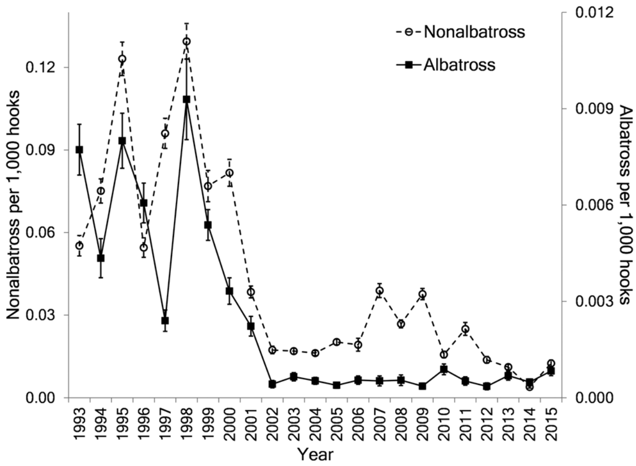

Figure 1. The annual weighted mean bycatch rate of albatrosses and nonalbatross species in all Alaskan longline fisheries combined from 1993 to 2015 derived from North Pacific Observer Program data (error bars, weighted SE).

(Supporting Information). Continuous variables, except year, were centered (value minus the mean).

We modeled BPUE in the 2 fisheries that were sampled most—sablefish and cod fisheries. Nonalbatross BPUEs were modeled in both fisheries. Albatross bycatch, however, was modeled only in the sablefish fishery—the fishery with the highest albatross BPUE. Albatross BPUE was not modeled in the cod fishery because albatross bycatch was rare (0.07–0.7% of sets) and BPUE was exceedingly low, despite accounting for 88% of hooks observed. Halibut and turbot were not modeled because the halibut fishery has been monitored only since 2013 and effort in the turbot fishery was low in the postadoption era. In all 3 cases, we generated models for the entire 23-year data set to compare BPUE before and after streamer-line adoption and for the 14 years after streamer-line adoption to explore variables affecting seabird bycatch.

Results

Observers reported 45,337 seabirds caught in >0.25 million sets of a billion hooks (Table 1). The BPUE of albatross and nonalbatross species dropped precipitously from highs in the middle to late 1990s to new lows starting in 2002 with the voluntary adoption of streamer lines (Fig. 1).

Before and After Streamer-Line Adoption

Over the 9 years prior to voluntary adoption of streamer lines, observers reported 31,988 seabirds caught during >98,000 sets of over 370 million hooks (mean BPUE = 0.086 [SE 0.002]) (Table 1). Albatrosses were 6.1% of observed seabird bycatch, and the remainder was nonalbatross species (93.9%) (Table 1). Albatross BPUE was highest in sablefish and turbot fisheries and lowest in cod fishery (Table 2). In contrast, BPUEs of nonalbatross species were similarly high in cod and turbot fisheries and lowest in sablefish fishery (Table 2).

Over the longer period after streamer-line adoption (14 years), observers reported 13,389 seabirds caught during over 164,000 sets of over 703 million hooks (mean BPUE = 0.019 [SE < 0.001]), a 78% decrease from before adoption (Table 1).

Models Before Versus After Streamer-Line Adoption

For the albatross and sablefish model, era, season, and area were retained in the count and binomial components of the final best-fit model (Supporting Information), meaning both the number and magnitude of bycatch events decreased significantly across seasons and areas after streamer lines were implemented in the sablefish fishery. Mean albatross BPUE decreased by over a factor of 3 between pre- and postadoption eras. The interaction between season and area was also significant in both parts of the model, suggesting that predicted occurrence and magnitude of bycatch events varied differently among the 4 geographic areas for the first and second halves of the season. The era–area interaction was significant in only the binomial component of our model, suggesting the likelihood of 0 bycatch events varied differently among 4 areas before and after streamer-line adoption.

For the nonalbatross sablefish model, era and area were included in the count and binomial components of the final best-fit model (Supporting Information), meaning both the number and magnitude of nonalbatross bycatch events decreased significantly across the 4 geographic areas after streamer lines were implemented in the sablefish fishery. Season was included in only the binomial component of our model, suggesting the likelihood of a bycatch event of a nonalbatross species was reduced across seasons but not the magnitude of the event. Mean nonalbatross BPUE decreased by over a factor of 2.6 between the pre- and postadoption eras. The only significant interaction was between era and area in the model's count component, suggesting the pattern of the magnitude of bycatch events of nonalbatross species varied differently among the 4 areas before and after streamer lines were implemented in the sablefish fishery.

For the nonalbatross Pacific cod model, only era was included in both the count and binomial components of the final best-fit model (Supporting Information), meaning both the number and magnitude of nonalbatross bycatch events decreased significantly after streamer lines were implemented in the Pacific cod fishery. Season was included in only the model's count component, suggesting the predicted magnitude of nonalbatross bycatch events

Table 1. Summary of observed (unextrapolated) longline effort[a] and seabird bycatch by species[b] before (1993 to 2001) and after (2002 to 2015) adoption of streamer lines in Alaskan longline fisheries.

	Preadoption		*Postadoption*		
Variable	*number*	*BPUE[c] (SE)*	*number*	*BPUE (SE)*	*BPUE decrease (%)[d]*
Hooks sampled (x 1,000)	370,458	–	703,120	–	–
Sets sampled	98,700	–	164,779	–	–
Sets with albatross (%)	12		0.2		
Sets with nonalbatross (%)	9		4		
Total albatross	1,959	0.0053 (0.0002)	392	0.0006 (0.0000)	88.7
Black-footed Albatross	310	0.0008 (0.0001)	135	0.0002 (0.0000)	75.0
Laysan Albatross	1,415	0.0038 (0.0002)	245	0.0003 (0.0000)	92.1
Short-tailed Albatross	3	0 (0)	4[e]	0 (0)	–
Unidentified albatross	231	0.0811 (0.0000)	8	0.0185 (0.0000)	77.2
Total nonalbatross	30,029	0.081 (0.0016)	12,997	0.018 (0.0004)	77.8
Northern Fulmar	18,999	0.0513 (0.0013)	6,816	0.0097 (0.0003)	81.1
Gulls	5,692	0.0154 (0.0005)	3,565	0.0051 (0.0002)	66.9
Shearwater spp.	1,168	0.0032 (0.002)	1,563	0.0022 (0.0001)	31.3
Other[f]	4,170	0.0113 (0.0005)	1,053	0.0015 (0.0001)	86.7
Total birds	31,988	0.086 (0.0017)	13,389	0.019 (0.0004)	77.9

[a] *Hooks, sets sampled, and number of sets with albatross and nonalbatross bycatch.*
[b] *Bird numbers, weighted mean bycatch per unit effort (BPUE) (birds/1,000 hooks), and weighted SE.*
[c] *Birds/1,000 hooks.*
[d] *Percent change in BPUE after streamerline adoption.*
[e] *One additional Short-tailed Albatross was caught but excluded from this analysis based on our criteria to exclude sets with <20% of the hooks monitored.*
[f] *Includes unidentified birds (97%),* Rissa *spp. (1.5%), Alcidae (1.2%),* Stercorarius *spp. (0.1%), and* Oceanodroma *spp. (<0.1%).*

was variable among seasons but not the predicted likelihood of an event. The mean nonalbatross BPUE in the cod fishery decreased by more than a factor of 3.7 between the pre- and postadoption eras. The only significant interaction was between era and season in the model's count component, suggesting the magnitude of bycatch events of nonalbatross species varied differently among era-season pairings.

Postadoption Models

In the albatross sablefish model, season and area were included in the count and binomial components of the final best-fit model (Supporting Information), whereas year— a continuous variable— was significant in only the count component and time of day was significant in the binomial component of the model. No significant first-order interactions were detected. Although predicted mean albatross BPUE decreased in the postadoption era by 68.5% compared with the preadoption era, it steadily and significantly increased across the 14 years after streamer-line adoption (Fig. 2b). The increasing trend was consistent across the 4 geographic areas; albatross BPUE were highest in the Bering Sea and Aleutian Islands (BSAI) but similar among the 3 Gulf of Alaska (GOA) areas. Albatross BPUE was lower in all but the central-GOA (C-GOA) in the second half of the fishing season; the most dramatic reduction was in the BSAI (>4 times) and the western-GOA (W-GOA) (>3 times) (Supporting Information). Albatross BPUE was 5 times or 80% lower when hooks were deployed at night (0.002 BPUE; SE 0.003) than when hooks were deployed during the day (0.011 BPUE [SE 0.008]).

In the nonalbatross sablefish model, year and area were included in the count and binomial components of the best-fit model (Supporting Information). Three predictor variables absent from the albatross and sablefish model were retained in the count component of the nonalbatross model (depth, total hooks, target fish CPUE) and 1 (season) in the binomial component. Retained interactions were area $*$ total hooks in the count component and area $*$ season in the binomial component. Unlike

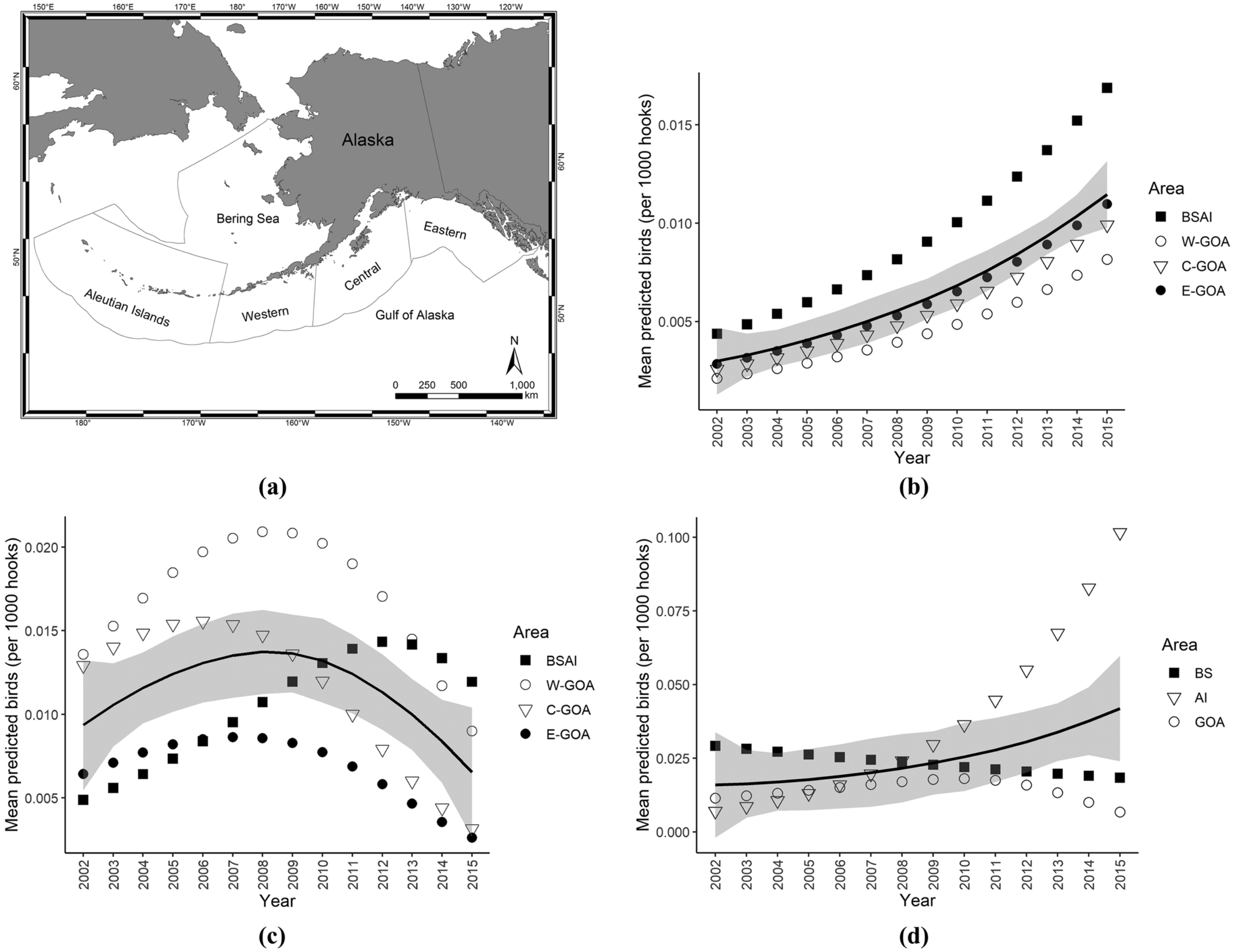

Figure 2. (a) Major management region of Alaskan longline fisheries and mean annual predicted rate of seabird bycatch overall (black line) (gray shading, 95% CI) and for (b) albatrosses (Laysan, Black-footed, Short-tailed) in the sablefish fishery, (c) nonalbatross species (primarily Northern Fulmar, gulls, and Short-tailed and Sooty Shearwaters) in the sablefish fishery, and (d) overall seabird species in the Pacific cod fisheries after streamer-line adoption (2002 to 2015) (BSAI, Bering Sea and Aleutian Islands; GOA, Gulf of Alaska; W, western; C, central; E, eastern; BS, Bering Sea).

albatross bycatch, BPUE of nonalbatrosses in the sablefish model showed a curvilinear trend; overall BPUE increased steadily from 2002, peaked at 0.014 BPUE (SE 0.009) in 2008, and declined steadily to a low of 0.007 BPUE (SE 0.002) in 2015 (Fig. 2c). The curvilinear trend was evident across the 4 geographic areas, but the year in which peaks occurred varied by area. In the W-GOA, BPUE matched the overall pattern. Rates in the C-GOA and E-GOA peaked in 2006 and 2007, respectively, and the BSAI peaked in 2012. Nonalbatross BPUE was more than 50% lower in the second half of the fishing season in all areas except the BSAI, where rates were 22% higher in the early season (Supporting Information). Unlike albatross BPUE, time of day was not retained in the final model.

In the nonalbatross Pacific cod model, year, time of day, area, and depth were included in the count and binomial components of the best fit model. Season was significant only in the model's count component (Supporting Information). Two interactions were retained: area ∗ year interaction in both components of the model and area ∗ season in the count component. Although predicted mean nonalbatross species BPUE decreased after adoption by 73% compared with before adoption, like albatrosses in the sablefish fishery, the predicted BPUE of nonalbatross species in the cod fishery steadily and significantly increased in the Aleutian Islands (AI) over time after streamer lines were adopted (Fig. 2d). In contrast, the BS showed a decreasing trend, and the GOA

Table 2. Summary of seabird bycatch[a] and sampling effort (hooks and sets) by target species recorded by fishery observers for albatrosses and nonalbatross seabird species before (1993 to 2001) and after (2002 to 2015) adoption of streamer lines in Alaskan longline fisheries.

	Preadoption						*Postadoption*					
	albatross		*nonalbatross*		*sampled*	*sets with birds (%)*	*albatross*		*nonalbatross*		*sampled*	*sets with birds (%)*
Target species	number	BPUE (SE)	number	BPUE (SE)	hooks x 1,000 (sets)	albatross, nonalbatross	number	BPUE (SE)	number	BPUE (SE)	hooks x 1,000 (sets)	albatross, nonalbatross
All	1,959	0.0053 (0.0002)	30,029	0.081 (0.0016)	362,948 (94,620)		392	0.0006 0	12,997	0.018 (0.0004)	698,040 (161,504)	
Sablefish	630	0.024 (0.002)	942	0.036 (0.002)	26,209 (13,014)	3, 4	230	0.007 (0.001)	437	0.014 (0.001)	30,841 (21,275)	0.9, 1.3
Pacific cod	829	0.003 (<0.001)	27,309	0.086 (0.002)	317,882 (74,832)	0.7, 11	116	0.0002 (0)	11,750	0.018 (<0.001)	650,682 (130,381)	0.07, 5
Turbot	355	0.019 (0.002)	1,582	0.084 (0.006)	18,857 (6,774)	3, 8	12	0.001 (<0.001)	699	0.048 (0.004)	14,413 (5,167)	0.2, 7
Halibut[b]	-	-	-	-	-		7	0.003 (0.001)	14	0.007 (0.002)	2,104 (4,681)	0.1, 0.3

[a]*Bird numbers, weighted mean bycatch per unit effort (BPUE) (birds/1,000 hooks) and weighted SE.*
[b]*Rates calculated using 2013–2015 only.*

showed a subtle curvilinear trend peaking in 2010. In the second half of the fishing season, BPUEs were considerably higher in the BSAI (2 times) and the GOA (1.5 times) compared with the first half of the season, but there was little difference in seasonal BPUE in the AI. Nonalbatross species BPUE was 29.5% lower when hooks were set at night (0.021 BPUE [SE 0.016]) than when they were deployed during the day (0.029 BPUE [SE 0.003]).

Time-of-Day Effects

Mean BPUE per observation of all but 1 seabird species or species grouping were significantly lower (by >50%) for night sets (all target species combined), whereas the mean nighttime CPUE for target and nontarget fish species in the sablefish and cod fisheries were significantly higher (4.7% to 16.6%) relative to daytime sets (Table 3). The positive effects of night setting were most dramatic for the albatrosses and shearwaters, whose BPUEs were >85% lower at night. Similarly, the positive effects on target CPUE were greatest in the cod fishery. Cod nighttime CPUE was 10.6% higher than daytime; however, this was offset by an even higher (16.6%) mean nighttime CPUE of nontarget species. The nighttime CPUE of sablefish and sablefish fishery nontarget fish species were 6.7% and 4.7% (respectively) higher than daytime sets. Among seabirds, Northern Fulmars were the exception— they were caught at significantly higher rates (by 40.4%) at night.

Individual Vessel Effect

In both the sablefish and cod fisheries, seabird bycatch was rare to absent on most vessels. Of monitored vessels from 2013 to 2015 that targeted sablefish (178 vessels) and cod (98 vessels), 28% and 33%, respectively, caught seabirds. Of the vessels with seabird bycatch, a few accounted for a disproportionate share. In the sablefish fishery, 3 vessels accounted for 46% of the 94 albatrosses caught, and in the cod fishery 3 vessels accounted for 78% of the 18 albatrosses caught. The same trend was true for nonalbatross species. 3 vessels accounted for 51% of the 49 birds caught in the sablefish fishery, and 3 vessels accounted for 31% of the 1,524 birds caught in the cod fishery. Our ability to determine whether individual vessels incidentally catch seabirds at anomalously high rates year after year was limited by the fact that few vessels were monitored in sequential years in both the sablefish (~18%) and cod (~33%) fisheries during this period.

Table 3. Simple mean (SE) seabird bycatch rate (BPUE) (birds/1,000 hooks) by seabird species or species groupings for all target species combined and fish catch per unit effort (CPUE) (kg/1,000 hooks) of target and nontarget fishes in the sablefish and cod longline fisheries for sets made during the day and at night after streamer-line adoption (2002 to 2015).

	Day		*Night*				
Seabird species	*BPUE/CPUE*	*SE*	*BPUE/CPUE*	*SE*	*Mann–Whitney U*	*p*	*Change (%)*
All albatrosses	0.003	0.0002	0.000	0.0001	3380200000	0.0000	−91.1
Black-footed Albatross	0.001	0.0002	0.000	0.0000	3373800000	0.0000	−97.1
Laysan Albatross	0.001	0.0001	0.000	0.0001	3376000000	0.0000	−86.8
Short-tailed Albatross	0.000	0.0000	0.000	0.0000	3369900000	0.3509	−93.8
All nonalbatrosses	0.023	0.0006	0.017	0.0007	3414800000	0.0000	−26.7
Northern Fulmar	0.008	0.0003	0.013	0.0006	3350000000	0.0000	40.4
Gulls	0.010	0.0005	0.003	0.0002	3404500000	0.0000	−73.7
Shearwater spp.	0.004	0.0002	0.000	0.0001	3397500000	0.0000	−87.8
Other*	0.002	0.0001	0.001	0.0001	337860000	0.0000	−51.4
Fish catch							
Sablefish target	273.3	1.9	292.7	3.2	42949000	0.0000	6.7
Sablefish nontarget	321.7	2.8	337.5	4.5	43448000	0.0000	4.7
Pacific cod target	464.4	1.2	519.2	1.1	1836200000	0.0000	10.6
Pacific cod nontarget	144.2	0.8	161.0	0.5	1787700000	0.0000	16.6

**Includes unidentified birds (97%),* Rissa *spp. (1.5%), Alcidae (1.2%),* Stercorarius *spp. (0.1%), and* Oceanodroma *spp. (<0.1%).*

Discussion

Before versus After Streamer-Line Adoption

Our case study is unique and revealing in several ways. Alaskan longline fisheries represent one of the few cases where sharp reductions in seabird BPUEs demonstrated in research translated into sharp reductions in seabird BPUEs (77–90%) when results were applied to an active commercial fishery. Comparing the mean bycatch between the pre- and poststreamer-line periods in published reports of total estimated bycatch from fishing effort and BPUE data (Fitzgerald et al. 2008; Eich et al. 2016), we estimate that these reductions in bycatch prevented the mortality of 675 albatrosses/year (1,001 albatrosses/year [SE 155] preadoption versus 326/year [SE 49] post adoption) and 9,399 nonalbatrosses/year (14,845 birds [SE 2,008] preadoption versus 5,446 birds/year [SE 598] postadoption) despite a 47% increase (203,892,000 hooks [SE 9,445,000] preadoption versus 299,825,000 [SE 16,342,000] postadoption) in annual mean fishing effort through 2006, the last year for which total fishing effort was estimated (Supporting Information).

We attribute the rapid adoption of streamer lines and seabird bycatch reduction to several factors. The threat of lost fishing opportunity should a handful of endangered Short-tailed Albatross be caught and the loss of baits to birds motivated fishers to participate in the research and to act quickly on the outcome. At the same time, industry leaders were proactive in calling for required conservation measures in their fisheries and for comprehensive studies to find long-term solutions. The manner in which the initial research program (Melvin et al. 2001) was carried out also played an important role. It was highly collaborative; industry leaders and innovators identified options for testing and were integrally involved in structuring and hosting the research trials; conducted during standard fishing operations; large in scale (>7.5 million hooks in 2 fleets and 8 vessels); and used controls (no deterrent) to yield unambiguous results in 2 years. The research effort was well funded through fishery and wildlife management agencies and had their solid support. Results were shared following each phase of research trails, and industry input was central to formulating subsequent trials and final management recommendations. The streamer-line solution was affordable, safe, and applicable to all vessel classes in this diverse fleet and did not negatively affect CPUE (Melvin et al. 2001). Extensive outreach through industry meetings, fliers, and a video and making streamer lines available to the fleet at no cost all contributed to this outcome.

After Streamer-Line Adoption

In the 14 years after streamer-line adoption, the magnitude and trends in seabird BPUE varied by target fishery and seabird species groupings. The highest albatross BPUE was in the sablefish fishery – 35 times higher than the cod fishery BPUE and 7 times higher than the turbot fishery BPUE. The sablefish fishery is a deep-water fishery at the continental shelf break in the GOA and AI, where albatrosses are most abundant (Kuletz et al. 2014). The highest BPUE of the nonalbatross species was in the turbot fishery – 3 times that of the sablefish and cod fisheries. The turbot fishery is also a shelf-break fishery, but centered in the northern BS where Laysan albatross and black-footed albatross are relatively uncommon (Eich et al. 2016). Alaskan longline fisheries were a composite of target fisheries with unique seasons and fishing grounds, which means each fishery encounters and interacts differently with the seabird species attending fishing operations. Consequently, analysis of BPUE for Alaskan fisheries are best conducted at the target-fishery level in order to detect meaningful trends.

Despite sharp declines in seabird bycatch following the adoption of streamer lines, albatross BPUE in the sablefish fishery and nonalbatross species bycatch in the cod fishery showed a significant increasing trend over time after streamer-line adoption. Although these trends are alarming, the highest mean rates in 2015 remained 3 (0.012 albatrosses BPUE) and 2 times lower (0.042 nonalbatross species BPUE) than that of the mean BPUE preadoption in the sablefish (0.036 BPUE) and cod (0.086 BPUE) fisheries, respectively. The increasing trend in albatross BPUE in the sablefish fishery was consistent across all 4 management areas, suggesting a pervasive, area-independent driver. In the sablefish fishery the annual bycatch trends of nonalbatross species varied in all areas and were uncoupled to trends in albatross BPUE, suggesting that in the same fishery albatrosses and nonalbatross species were responding to different forces. Although area and season were significant in nearly all our models, a clear pattern suggesting a coherent time-area management strategy across these fisheries was not evident (Supporting Information).

An explanation for the increasing trends in albatross bycatch was also not readily evident from our results. We suspect the few reported bycatch mortalities of Short-tailed Albatross after adoption (none until 2009 and 4 in 14 years, all in the cod fishery) may have led to a lessening of the urgency that prevailed in 2002. Over time, this, and possibly a lessening of the awareness of the need for seabird conservation, may have led to streamer lines not being deployed to specifications. Accordingly, a program of port-based outreach and free streamer-line distribution was renewed in 2015 to address this possibility. Other possibilities include a wider range of vessels in the observer program starting in 2013, changes in the distribution of fishing effort, reduced natural prey for seabirds, or seabirds habituating to streamer lines. Continued adaptive management of the fishery is essential to ensure seabird conservation is maintained.

Night setting is an accepted best practice to prevent seabird bycatch in longline fisheries globally (e.g., Løkkeborg 2011). However, few researchers considered the impact of night setting on the CPUE of target fishes. We found that night setting reduced BPUE of most seabird species and increased CPUE of target fish species, sablefish and cod. The BPUE of Northern Fulmar, the bird most caught in Alaskan longline fisheries, was the only seabird in this assemblage caught at significantly higher rates (by 40%) during night sets. Higher Northern Fulmar bycatch at night is consistent with Northern Fulmar bycatch in the cod fishery (Melvin et al. 2001), a finding that led fishery managers to eliminate night setting as a seabird-bycatch reduction measure in Alaskan longline fisheries. Higher BPUE of a seabird species at night versus during the day may be unique to Northern Fulmar in Northern Hemisphere fisheries and supports the contention that best practice recommendations should be area and fishery specific (Gladics et al. 2017).

Management and Conservation Implications

Night setting presents trade-offs. Although it is compelling that night setting reduced bycatch of most seabirds and increased CPUE of target fishes, several factors limit the potential of night setting as a conservation measure. The first is that an increase in Northern Fulmar and nontarget fish species bycatch during night setting fails to meet our basic criterion for best practice measures— reduce seabird bycatch without increasing the bycatch of other species. The second factor is that in high-latitude fisheries, such as those in Alaskan waters, hours of darkness are few from late Spring to early Fall, when effort peaks for sablefish and halibut, the fisheries with the highest albatross BPUE. The best application of night setting in Alaskan waters could be voluntary implementation in areas where endangered Short-tailed Albatross are present or when albatrosses dominate the seabird assemblage and Northern Fulmars are few. This trade-off between the conservation of species of special conservation concern, the albatrosses, versus an abundant species with minimal conservation concern, Northern Fulmar, creates a challenge to fishery managers. In a fishery where the take of 6 Short-tailed Albatrosses could close a US$300 million fishery with over 1,000 vessels, managers might opt for albatross conservation as the overriding priority.

Conservation measures should be fishery specific. What is unique to the Alaskan longline fisheries is that seabird conservation was achieved using a single technical measure—streamer lines. This stands in contrast to the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) demersal longline fishery for Patagonian toothfish (*Dissostichus eleginoides*), the iconic fishery in which best practices for preventing seabird bycatch in demersal longline fisheries were pioneered. In that fishery, seabird bycatch decreased sharply when seasonal closures to prohibit fishing during the seabird-breeding season were added to technical measures (streamer lines, line weighting, night setting) that had been in place for several years (Waugh et al. 2008). In contrast, sharp declines in seabird BPUE in Alaskan longline fisheries occurred almost immediately following research and without requirements for night setting, line weighting, or seasonal closures. We found that in Alaska seasonal closures are unlikely to contribute to bycatch reductions and that night setting presents unwelcomed trade-offs. Experimental research in the Alaskan fisheries has consistently demonstrated that combining streamer lines with line weighting did not further reduce the BPUE of albatrosses and other surface-foraging birds relative to streamer lines alone (Melvin et al. 2001; Dietrich et al. 2008).

Differences between the Alaskan and CCAMLR fisheries may be explained by differences in the composition of the seabird assemblage interacting with these fisheries. In the southern oceans, a greater diversity of albatrosses and petrels attend fishing operations, which overlap the foraging grounds of many of these birds when they are breeding. Also, most birds in the southern oceans assemblage can access baited hooks farther below the surface than birds that attend vessels in Alaskan waters. These factors make the Southern Hemisphere seabird assemblage more difficult to deter, thus requiring a multiple conservation measures to successfully prevent fishery mortalities. These collective observations strongly suggest that conservation measures should be tailored to specific fisheries and that universal best practice prescriptions should be the starting point for fisheries specific vetting via experimental research and adaptive management.

Two earlier studies exploring drivers of seabird BPUE in Alaskan longline fisheries show that vessel was most influential factor explaining variation in seabird BPUE (Dietrich et al. 2009; Dietrich & Fitzgerald 2010). Our analysis identified 3 vessels that accounted for 46% to 78% of the albatross bycatch and 31% to 51% of the nonalbatross species bycatch over 3 years, depending on the fishery. The reasons for anomalously high BPUE by these vessels are unknown. We posit that the greatest potential to further reduce seabird bycatch in Alaskan longline fisheries lies with reducing the BPUE on individual vessels with high BPUE. Although this could possibly be achieved through punitive measures, we suggest nonpunitive measures, such as outreach and education, aimed at these vessel operators be a first step. It could be that the operators of vessels with high BPUE are unaware of their performance relative to their peers and may lack understanding of the need for seabird conservation or how best to achieve it. Given most vessels do not catch birds, this strategic outreach approach could direct scarce resources to where they are most needed.

Our findings strongly suggest that routine analysis and reporting of observed seabird BPUE by target fishery is central to detecting trends and reducing or maintaining reductions in seabird bycatch, independent of changes in fishing effort. With routine reporting, corrective actions can be identified and taken quickly. Estimating total bycatch of a species is also important to assess population-level effects, but these extrapolations are less reliable in detecting trends because of large uncertainty in the number of hooks deployed. Ultimately, however, both BPUE and estimates of total bycatch by species or species group are needed to evaluate seabird conservation in a fishery. The increasing trend in BPUE of albatrosses and nonalbatross species in 2 different fisheries following sharp reductions in overall BPUE allowed us to alert fleets and fishery managers so that corrective measures could be pursued.

Although we could not definitively identify the reasons for the increase in BPUE in two fisheries following streamer-line adoption, we believe continued outreach to fleets on the need for seabird conservation, changing trends in BPUE in their fisheries, and techniques to reduce seabird bycatch could stabilize and reverse these unwelcome trends. As fishing crews turnover and Short-tailed Albatross populations grow, the risk that small incidental bycatch limits may be exceeded could increase. Ongoing research and outreach is fundamental to minimizing these risks and keeping seabird conservation awareness a constant in fishing operations.

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Supporting Information

Definitions of model variables (Appendix S1); variables tested in zero-inflated negative binomial models by target species and seabird groupings (Appendix S2); final and competing 0-inflated negative binomial models with associated ΔAICs for the full time series (Appendix S3); final and competing 0-inflated binomial models with associated ΔAICs after streamer-line adoption (Appendix S4); estimated annual total bycatch of albatrosses, nonalbatrosses, and total birds and fishing effort before and after adoption of streamer lines (Appendix S5); and mean predicted BPUEs by major fisheries management area and season (Appendix S6) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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