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Original Article

Assessment of seabird bycatch in the US Atlantic pelagic longline fishery, with an extra exploration on modeling spatial variation

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With the observer data from the National Marine Fisheries Service Pelagic Observer Programme (POP) and the logbook data from the US Atlantic pelagic longline fishery, we estimated the seabird bycatch in the fishery during 1992–2012. The POP observed 13 847 longline sets, with a total of 141 seabirds captured on 74 sets. The overall nominal catch rate was 0.0102 birds per set and 0.014 birds per 1000 hooks. We applied a random year effect model (RYEM) for analysis of the whole study region that includes 11 fishing zones. Extrapolating from the observed seabird bycatch, we estimated a total of 2255 seabirds captured on average (coefficient of variation CV = 14.72%) by the total fleet from 1992 to 2012. The highest estimate of seabird bycatch occurred in the middle Atlantic bight (MAB), followed by the northeast coast (NEC). Estimated seabird bycatch, by season, was higher in summer, fall, and winter than in spring. Longline sets targeting a mixed group of species caught the majority of the total seabird bycatch, and longline sets targeting swordfish and tuna also caught more seabirds than those sets targeting other species. To incorporate spatial variation into parameter estimation, allowing parameters to vary spatially, we applied a spatial expansion model (SEM) to data for the three fishing zones with the most observed seabird bycatch, the NEC, the MAB and the south Atlantic bight. When compared with the estimates from the RYEM (145–1049 seabirds with a CV of 16.4–23.5%), the SEM produced higher estimates (155–1489 seabirds) of the total seabird bycatch for each of these areas and a larger CV (19.1–65.4%). The RYEM may be appropriate for seabird bycatch assessment when spatial variation is not a concern; the SEM could be an alternative when observed data vary greatly over space.

Keywords: random year effect, seabird bycatch, spatial expansion, spatial nonstationarity

Introduction

Seabird bycatch and the associated seabird mortality in longline fisheries are of increasing concern in fisheries management and marine conservation (Furness, 2003; Phillips *et al.*, 2010; Anderson *et al.*, 2011; Huang, 2015). Seabirds are drowned when hooked or entangled (Brothers *et al.*, 1999a; Gilman, 2001) on sinking lines. Seabird populations are particularly vulnerable to fisheries incidental mortality due to late maturity and low reproduction rates. Concern regarding the sustainability of seabird populations, especially the populations of threatened and endangered species, has led to the development of action plans (e.g. Department of Commerce, 2001; Food and Agriculture Organization (FAO), 2008; BirdLife International and ACAP, 2009) and research programs to reduce seabird bycatch in longline fisheries. This study was part of the National Oceanic and Atmospheric Administration (NOAA) Fisheries National Seabird Programme for seabird bycatch reduction.

The Pelagic Observer Programme (POP) at the National Marine Fisheries Service Southeast Fisheries Science Center has monitored the US Atlantic pelagic longline fishery since 1992. The fishery operates in 11 specified fishing zones (Figure 1; Lee and Brown, 1998), and targets tunas (*Thunnus* spp.), swordfish (*Xiphias gladius*), dolphinfish (*Coryphaena hippurus*), and sharks (Selachimorpha). The POP collects fishing and environmental information from randomly selected fishing trips and attempts to cover 8% of the longline fishing trips in each fishing zone and calendar quarter (Diaz *et al.*, 2009). Reporting of each fishing trip is required in the US Atlantic pelagic longline fishery, and thus the reporting rate of fishery logbook data is 100%.

Spatial patterns of seabird bycatch are observed in the POP (Figure 1), and should not be overlooked when developing assessment models. In this study, spatially varying relationships between biological processes and environmental factors (e.g. the intercept and slope parameters in the generalized linear model), also termed spatial non-stationarity, were explored with the spatial expansion model (SEM; Brunsdon *et al.*, 1996), As one of the early and relatively simple techniques to explore spatial nonstationarity, the SEM models each parameter as a function of location, which allows parameters to vary over space (Casetti, 1972; Casetti and Jones, 1992). Spatial modeling of the seabird bycatch is challenging and computationally costly because of the large dataset and excessive zeros that result in unbalanced data and limited spatial information on capture events.

In this study, we aimed to (i) develop a random year effect model (RYEM) using the 1992–2012 observer data to estimate seabird bycatch for 11 fishing zones by extrapolating to the pelagic longline fishery logbook data; (ii) investigate the spatial and temporal hotspots of seabird bycatch; and (iii) explore the potential to improve estimation with a SEM for the three contiguous fishing zones with highest seabird bycatch. These zones are the northeast coast (NEC, an area with a latitude from 35 to 50°N and a longitude between −71 and −60°W), the middle Atlantic bight (MAB, an area with a latitude north to 35°N and a longitude between −82 and −71°W) and the south Atlantic bight (SAB, an area with a latitude between 30 and 35°N and a longitude west to −71°W).

Material and methods

Observer data and fishery logbook data

The analyzed POP data from 1992 to 2012 contained 13 847 longline sets, among which only 74 sets caught 141 seabirds; therefore, >99% zero observations were present in the POP data (Figure 1). Only those explanatory variables and total fishery effort that were consistently and reliably recorded in common between the POP and logbook data could be used to extrapolate from the observed bycatch to total estimated bycatch. Therefore, we restricted extrapolation to the 230 691 logbook longline sets (out of the 239 966 longline sets that we received) that had sufficient information to match a refined set of POP variables.

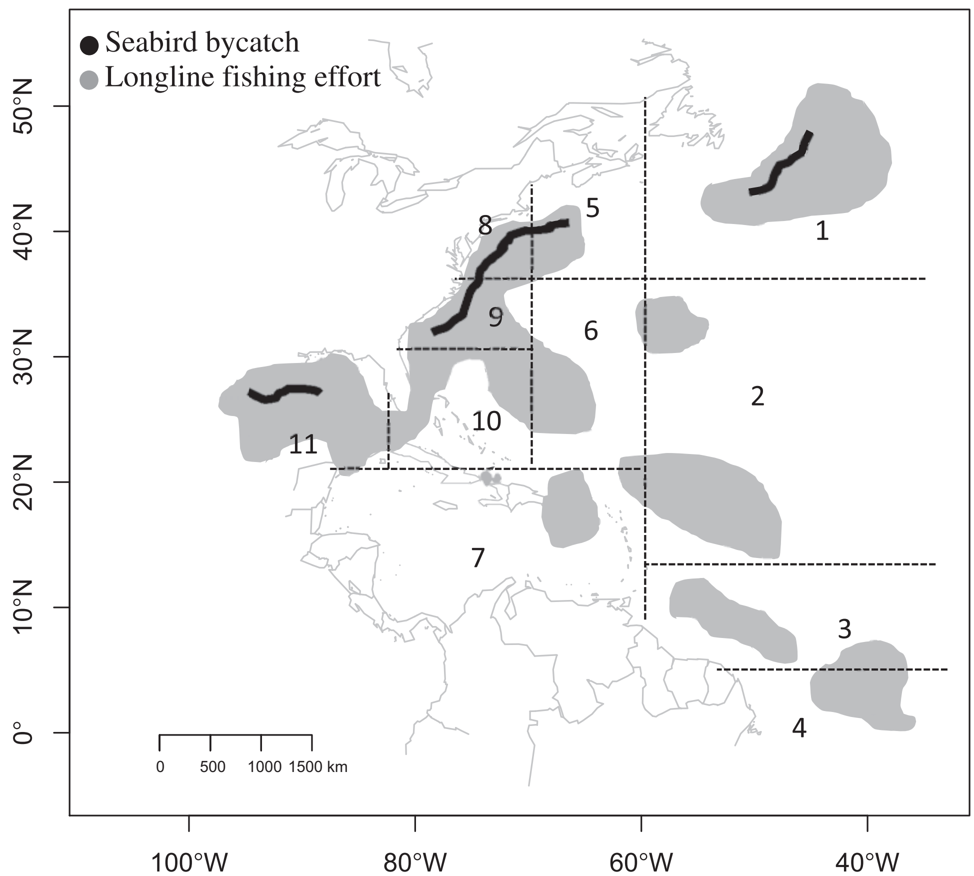

Figure 1. Generalized spatial distribution of the observed longline sets (grey areas) and those with seabirds caught (black strips) in all 11 fishing zones during 1992–2012. 1. NED, 2. NCA, 3. TUN, 4-Tuna South (TUS), 5. NEC, 6. SAR, 7-Caribbean region (CAR), 8. MAB, 9. SAB, 10. Florida east coast (FEC), 11-Gulf of Mexico (GOM). The three zones with highest seabird bycatch are the NEC, MAB, and SAB.

Predictor variables for model development

The set of provisional predictor variables that we considered for model development included season, latitude, longitude, water temperature, target species, and number of hooks set. Spatial and seasonal patterns of seabird bycatch have been observed in the POP data, with 97% of seabirds caught along the east coast of the United States and 99% of seabirds caught in summer through winter (Figure 1, Supplementary Tables S2 and S3). The importance of spatial and seasonal effects on seabird bycatch has also been recognized in other studies (e.g. Klaer and Polacheck, 1998; Brothers *et al.*, 1999b; Jimenez *et al.*, 2010). The study region of 11 fishing zones extended from the NEC of the United States to the Gulf of Mexico, over several temperature zones. Thus, the predictor, water temperature, may have been a factor that characterized the large-scale distribution of seabirds. The predictor, target species, may have embodied information about the fishing practices particular to fishing for each target species, e.g. bait, dropline depth, day-night setting, and these previously have been identified as factors influencing seabird bycatch in longline fishing (Klaer and Polacheck, 1998; Brothers *et al.*, 1999b). We could not use these fishing characteristics directly because they were absent from the logbook data. The variable, number of hooks set, is a measure of fishing effort, presuming that more hooks could lead to more captures of both target and bycatch species.

The specific predictors ultimately included in each model (Table 1) were selected from the set of provisional predictors through a forward stepwise procedure based on Akaike Information Criterion (AIC, Akaike, 1974; Burnham and Anderson, 2002). At each step, the predictor that most greatly reduced the AIC value was added to the null model, and this process was repeated until inclusion of an additional predictor would not substantially improve model performance (i.e. the decrease in AIC was less than five). In the stepwise selection process, our models frequently selected longitude, latitude, season, target species, and water temperature to explain the variation in seabird bycatch data.

RYEM for the whole study region (11 fishing zones)

Because zero observations made up more than 99% of the POP data, we applied the delta model approach to deal with the excessive zeros (Lo *et al.*, 1992; Stefansson, 1996; Fletcher *et al.*, 2005). Following the delta approach, the model we used for seabird bycatch consisted of two sub-models, one sub-model (termed the positive sub-model) to analyze only positive longline sets (i.e. the longline sets with at least one seabird captured) and the other sub-model (termed the probability sub-model) to estimate the probability of catching a seabird. The product of estimates from these two sub-models gives the final estimate, i.e. the number of seabirds caught on a longline set. We modeled year as a random effect in the probability sub-model because, in our previous work (Li and Jiao, 2011, 2012), we determined that the RYEM performed best according to its lowest AIC value. Furthermore, a simulation study (Li and Jiao, 2013) showed that the RYEM produced more accurate and more precise estimates than a fixed year effect model for seabird bycatch assessment. We did not consider random year effect in the positive sub-model because the number of positive longline sets was too small to support incorporating a random year effect.

The positive sub-model was a generalized linear model in which we assumed the logarithm of positive catch per longline set to follow a normal distribution with an identity link:ln(number of seabird bycatch per longline set) = intercept + number of hooks.

Table 1. List of predictors that were included in the models.

Predictor	Type	Categories/mean
Season	Categorical	Spring, Summer, Fall, Winter
Target species	Categorical	Mixed, Swordfish, Tuna, Shark, Dolphinfish
Year	Categorical	1992–2012
Latitude (°N)	Continuous	30.4
Longitude (°W)	Continuous	−79.3
Number of hooks	Continuous	725
Water temperature (Fahrenheit)	Continuous	76.7 (sea surface temperature)

The probability sub-model was a generalized linear model in which we assumed the events of capturing or not capturing a seabird on a longline set to follow a binomial distribution with a logit link:

$$ln\left(\frac{p}{1-p}\right) = \text{intercept} + \text{latitude} + \text{longitude} + \text{season} + \text{target species} + \text{random year effect}.$$

where p is the probability of catching a seabird, and the random year effect follows a normal distribution with a mean of zero.

We developed the RYEM using the POP data, and applied this model to the fishery logbook data to extrapolate from the observed seabird bycatch to the total estimated seabird bycatch for the entire 11-zone study area. A bootstrap approach with 1000 iterations was used to estimate the uncertainties in estimated seabird bycatch.

SEM for the three fishing zones with the highest seabird bycatch

We developed a SEM to estimate seabird bycatch for the three fishing zones with the highest seabird bycatch (Figure 1), i.e. the NEC, the MAB, and the SAB. The SEM expands parameters to be a function of location (u_i, v_i), where (u_i, v_i) denotes the geographical coordinates of the ith location (longitude, latitude), so that parameter estimates vary over space, and the spatial non-stationarity is explored (Casetti, 1972; Casetti and Jones, 1992). We employed a first order linear polynomial function as the expansion function because of limited positive catch data, and thus each of the parameters in the model was expanded as:

$$\beta(u_i,\ v_i) = a_0 + a_1 u_i + a_2 v_i$$

where a_0, a_1, a_2 are parameters in the expansion function, to determine a parameter β for the ith location. The parameter β can be any parameter in the model, and in our case, the parameters to expand included the intercept and the coefficient for each explanatory variable in a generalized linear model.

We developed a global SEM in which explanatory variables were selected using data from all three zones and applied this global SEM to the three zones combined. We also developed a localized SEM for each zone in which explanatory variables were selected using only data from that zone and applied this localized SEM to that zone. As the result of a stepwise process that

Table 2. A list of seabird species caught in the POP by area

Family	Species	NED	NCA	TUN	TUS	NEC	SAR	CAR	MAB	SAB	FEC	GOM	Total
Shearwater (Procellariidae)	Great shearwater (*P. gravis*)	1	0	0	0	7	0	0	17	0	0	0	25
	Cory's shearwater (*Calonectrisdiomedea*)	0	0	0	0	0	0	0	0	1	0	0	1
	Other Procellariidae*spp.*	0	0	0	0	1	0	0	0	0	0	0	1
Storm petrel (Hydrobatidae)	Hydrobatidae spp.	0	0	0	0	0	0	0	1	0	0	0	1
Pelican (Pelecanidae)	Brown pelican (*Pelecanus occidentalis*)	0	0	0	0	0	0	0	0	0	0	1	1
Gannet (Sulidae)	Northern gannet (*M. bassanus*)	1	0	0	0	3	0	0	5	2	0	0	11
Gull (Laridae)	Laughing gull (*Larus atricilla*)	0	0	0	0	0	0	0	0	1	0	1	2
	Herring gull (*Larus argentatus*)	0	0	0	0	0	0	0	11	1	0	0	12
	Black-backed gull (*Larus marinus*)	0	0	0	0	0	0	0	10	0	0	0	10
	Other Laridae spp.	0	0	0	0	2	0	0	21	0	0	0	23
Unidentified		2	0	0	0	28	0	0	10	12	0	2	54
Total		4	0	0	0	41	0	0	75	17	0	4	141

NED, Northeast district; NCA, North Central Atlantic; TUN, Tuna North; TUS, Tuna South; NEC, Northeast coast; SAR, Sargasso region; CAR, Caribbean region; MAB, Middle Atlantic bight; SAB, South Atlantic bight; FEC, Florida east coast; GOM, Gulf of Mexico.

determined which parameters were selected for each model, the global SEM took the form:

$$\text{Positive sub-model: } \ln(\text{number of seabird bycatch per longline set}) = \text{intercept} + \text{number of hooks},$$

$$\text{Probability sub-model: } ln\left(\frac{p}{1-p}\right) = \text{intercept} + \text{water temperature} + \text{season} + \text{target species}.$$

The three localized SEMs were constructed as follows:

$$\text{Positive sub-model for NEC: } \ln(\text{number of seabird bycatch per longline set}) = \text{intercept} + \text{number of hooks},$$

$$\text{for MAB: } \ln(\text{number of seabird bycatch per longline set}) = \text{intercept} + \text{number of hooks} + \text{water temperature},$$

$$\text{for SAB: } \ln(\text{number of seabird bycatch per longline set}) = \text{intercept};$$

$$\text{Probability sub-model for NEC: } ln\left(\frac{p}{1-p}\right) = \text{intercept} + \text{year},$$

$$\text{for MAB: } ln\left(\frac{p}{1-p}\right) = \text{intercept} + \text{water temperature} + \text{season},$$

$$\text{for SAB: } ln\left(\frac{p}{1-p}\right) = \text{intercept} + \text{water temperature} + \text{season} + \text{target species}.$$

We calculated the CV, a measure of precision, for each of our bycatch estimates because the National Marine Fisheries Service (NMFS)'s National Bycatch Strategy (NMFS, 2004) made CV a major criterion for evaluating estimation approaches for the bycatch of U.S. fisheries. Based on the recommendation of the National Working Group on Bycatch (NWGB), the NMFS strategy report set a CV goal, or threshold, of no more than 20% to 30% for bycatch estimates of both fishery species and protected species. This has been considered a reasonable uncertainty level in fisheries data (Walters, 1998). A lower value of CV indicates a more precise estimate. To determine whether the estimated seabird bycatch significantly differ across regions and seasons, we used the Tukey's range test for multiple comparisons of the mean estimated seabird bycatch among regions and seasons.

Results

A total of 13 847 pelagic longline sets was observed in the POP during the period of 1992–2012 (excluding the sets with erroneous records, e.g. the sets with zero hooks), among which 74 sets caught 141 seabirds (Supplementary Table S1). The overall nominal catch rate was 0.0102 birds per set or 0.014 birds per 1000 hooks. The POP observer effort was concentrated in the Gulf of Mexico (GOM), MAB, SAB, and Florida east coast (FEC), accounting for ∼80% of the total number of longline sets observed across all fishing zones (Supplementary Table S2). The NEC and MAB had the highest nominal catch rate (0.0437 birds per set or 0.0504 birds per 1000 hooks), followed by the MAB (0.0379 birds per set or 0.0505 birds per 1000 hooks) and the SAB (0.0126 birds per set or 0.0195 birds per 1000 hooks); no seabirds were caught in the North Central Atlantic (NCA), Tuna North (TUN), Tuna South (TUS), Sargasso region (SAR), Caribbean region (CAR), and FEC. The POP longline fishing effort in spring and summer was higher than in fall and winter (Supplementary Table S3); spring had the lowest nominal catch rate (0.0002 birds per set or 0.0003 birds per 1000 hooks). Of the 141 seabirds observed caught during 1992–2012, 53% (75 birds) were caught in the MAB, followed by 29% (41 birds) in the NEC and 12% (17 birds) in the SAB (Supplementary Table S2). Unspecified seabirds represented the most numerous group observed (54 birds), of which 52% were caught in the NEC (Table 2). Among those identified (not necessarily to species), seabirds and gulls were the most frequently captured, followed by shearwaters (Procellariidae spp., especially great shearwaters, *Puffinus gravis*), and the northern gannet (*Morus bassanus*, member of the Pelecaniformes family, Sulidae); most of the gulls (*Larus* sp.), shearwaters and northern gannets were captured in the MAB. Most of the seabirds not identified to species were captured prior to 2004, before seabird identification training was provided as part of the POP.

During the period of 1992–2012, 78% of the total pelagic longline fishing effort, in terms of sets, occurred in the Gulf of Mexico and along the eastern seaboard of the United States (i.e. the GOM, MAB, FEC, and SAB; Supplementary Table S4). Number of sets per year reached a maximum of 15 484 in 1995 before declining almost steadily through 2011. Effort in 2012

Table 3. Estimated annual seabird bycatch (in number) in the US Atlantic pelagic longline fishery (including 11 fishing areas) during 1992–2012, by the RYEM

Year	Mean	CV (%)
1992	79	40.51
1993	122	38.52
1994	140	35.00
1995	184	35.87
1996	57	19.30
1997	376	34.04
1998	130	49.23
1999	81	34.57
2000	63	38.10
2001	147	47.62
2002	169	46.75
2003	54	38.89
2004	111	36.94
2005	37	40.54
2006	73	41.10
2007	122	37.70
2008	43	34.88
2009	82	36.59
2010	36	36.11
2011	97	35.05
2012	52	36.54
Total	2255	14.72

CV, coefficient of variation.

Table 4. Estimated mean total seabird bycatch (in number) in the US Atlantic pelagic longline fishery by area and model

	RYEM		SEM (global)		SEM (localized)	
Area	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
NED	176	34.09	–	–	–	–
NCA	0	NA	–	–	–	–
TUN	0	NA	–	–	–	–
TUS	0	NA	–	–	–	–
NEC	620	18.39	708	23.08	791	19.11
SAR	1	100	–	–	–	–
CAR	1	0	–	–	–	–
MAB	1049	16.40	1446	20.11	1489	23.13
SAB	145	23.45	155	25.24	265	65.43
FEC	28	39.29	–	–	–	–
GOM	235	23.83	–	–	–	–

The RYEM was used for all 11 fishing areas, and the SEM was used for the three areas with highest seabird bycatch (i.e. NEC, MAB, and SAB). See the caption of Table 2 for abbreviation of fishing areas.

Table 5. Estimated seabird bycatch (in number) in the US Atlantic pelagic longline fishery by season

Season	Mean	CV (%)
Winter	564	23.94
Spring	22	104.55
Summer	1,004	19.42
Fall	664	24.40

The RYEM and data from all 11 fishing areas were used.

increased to 2001 levels (Supplementary Table S4). Fewer longline sets were deployed in winter than in the other three seasons, maximum longline effort was applied in summer (Supplementary Table S5).

Table 6. Estimated seabird bycatch (in number) in the US Atlantic pelagic longline fishery by target species

Target species	Mean	CV (%)
MIX	1,530	17.65
SWO	322	27.33
TUN	310	29.03
SHX	0	NA
DOL	93	54.84

The RYEM and data from all 11 fishing areas were used. MIX, mixed species, SWO, swordfish (*X. gladius*); TUN, tuna (*Scrombidae*); SHX, shark (*Selachimorpha*); DOL, dolphinfish (*C. hippurus*).

With the RYEM, we estimated the total number of seabirds caught in the US Atlantic pelagic longline fishery during the entire 21-year period of 1992–2012 to be 2255 on average (CV = 14.72%; Table 3). The highest annual estimate of seabird bycatch occurred in 1997 with 376 birds on average (CV = 34.04%). The fishing zones along the east coast had a significantly higher estimated seabird bycatch than other regions (p-value $\ll 0.05$). The MAB produced the highest seabird bycatch estimate with 1049 birds captured on average (CV = 16.4%), followed by the NEC (620 birds on average, CV = 18.39%), and the GOM (235 birds on average, CV = 23.83%; Table 4). The seabird bycatch estimates for summer, fall, and winter were statistically higher than in spring (p-value $\ll 0.05$), with the highest estimate in summer (1004 birds on average, CV = 19.42%; Table 5). Longline sets targeting a mixed group of species were estimated to produce the majority of the total seabird bycatch, with 1530 birds on average (CV = 17.65%); longline sets targeting swordfish and tuna also had a higher seabird bycatch than those sets targeting other species (Table 6).

For the three fishing zones with highest seabird bycatch, the global SEM model produced a 7-38% higher estimate of the total seabird bycatch than the RYEM, and the estimates by the local SEM were even higher, i.e. 28–83% higher than the RYEM (Table 4). All SEM models yielded estimates with larger CVs than the RYEM, among which the local SEM for the SAB area yielded estimates with the largest CV (65.43%).

Discussion

Spatial and temporal patterns of seabird bycatch

The assumption that biological and ecological characteristics vary over space seems particularly appropriate for seabirds because they are mobile and travel across a large habitat range. Many studies have shown the spatial and temporal impacts on seabird bycatch in longline fisheries (Klaer and Polacheck, 1998; Brothers *et al.*, 1999b; Jimenez *et al.*, 2010; Li *et al.*, 2012). Variation in seabird abundance across fishing zones may play a more important role than fishing effort in explaining the observed spatial and temporal patterns. For example, of the total fishing effort, 36%, occurred in GOM and only 17% occurred in MAB (Supplementary Table S4), but the estimated seabird bycatch in MAB was four times the estimate in the Gulf of Mexico (Table 4). The longline sets were well distributed across the four seasons, but we obtained a much lower seabird bycatch estimate in spring (Table 5). The variability in our spring estimate (105%) was four to five times higher than in the other seasons, even though observer coverage of effort, in terms of sets, was substantially higher in the spring (8.2%) than in the other seasons (5.2–5.4%).

The highest seabird bycatch estimate was for the MAB area and may be associated with the high seabird activity and diversity in this region. The MAB is characterized by its many submarine canyons and high freshwater inflow from rivers, and is influenced by the northward flowing Gulf Stream cruising close to the coast to Cape Hatteras, and the Labrador Current penetrating south to Cape Hatteras. The interaction between complex bottom topography, river plumes, and major currents create frontal zones that support great biodiversity and productivity. Some of the major currents have contrasting trajectories and temperatures, i.e. southward flowing cold Labrador Current and northeastward flowing warm Gulf Stream. Lee (1999) documented the presence of at least 49 seabird species at the outer continental shelf off Cape Hatteras in the southern MAB.

The highest annual estimate of seabird bycatch in 1997 (376 seabirds on average with a CV of 34.04%, Table 3) corresponded to the highest seabird catch rate that was observed in the POP data in 21 years (0.072 seabirds per set, and 0.104 seabirds per 1000 hooks, Supplementary Table S1). In 1997, a total of 11 observed longline sets captured 33 seabirds, among which all were captured in summer and 64% were captured in the NEC area. The logbook fishing effort in the NEC area (1494 longline sets) and in summer (4834 longline sets) was also highest in 1997 (Supplementary Tables S4 and S5). Thus, the intensive longline fishing in the hotspot area and season (i.e. the NEC area and the summer) may have contributed to such a high estimate of seabird bycatch in 1997.

The longline sets targeting mixed fish species produced the highest seabird bycatch estimates (Table 6). In the POP data, 42 of the 74 longline sets that captured seabirds were categorized as targeting mixed fish species. These 42 longline sets were deployed in a wide range of water depth (the maximum water depth 44–3475 m), and with a wide range of hook depth (maximum hook depth 16–59 m); this breadth of fishing range may have contributed to the high seabird bycatch on these longline sets. Additionally, ~79% of these 42 longline sets occurred before J-hooks were eliminated from the fishery by regulation (replaced with circle hooks) in August 2004. The frequent use of the J-hook prior to that time may have increased the chance of catching seabirds (Li *et al.*, 2012) because of the shape of the J-hook, i.e. a large gape and a barbed point parallel to shank (Beverly, 2006).

Model development

Development of the estimation models in this analysis was restricted by the explanatory variables that were recorded in common between the POP and logbook datasets. Some potentially important variables available in the POP data could not be used in our models due to missing corresponding information in the logbook data. For example, previous studies have suggested set time (Brothers *et al.*, 1999b; Belda and Sanchez, 2001), bait (Brothers *et al.*, 1999b; Foster *et al.*, 2012), and hook type/size (Li *et al.*, 2012) may be critical in catching seabirds. The exclusive use of circle hooks in place of J hooks since August 2004 (69 FR 40734) has proven to benefit seabird bycatch reduction (Li *et al.*, 2012). Reporting more of these important factors in the logbook would help improve seabird bycatch assessment in the future. The present shortcoming of the logbook data for estimating bycatch (of fish, turtles, marine mammals, seabirds) has been recognized in the Southeast Region section of the National Bycatch Report (NBR) Update 1 (NMFS, 2013).

In the NBR Update 1, the delta lognormal-based ratio method (hereafter "the ratio method") was applied to assess seabird bycatch. Both our method and the ratio method are based on the delta distribution (Pennington, 1983), which consists of two sub-models, one for the data with a seabird captured and the other one for estimating the probability of catching a seabird; the final estimate is product of the estimates from these two sub-models. The difference between our method and the ratio method lies in how to extrapolate from observer data to logbook data. The ratio method estimates the bycatch rates for each stratified fishing area and quarter of year, and then applies this ratio to the logbook data in the corresponding strata. In contrast, we directly estimated seabird bycatch from each logbook longline set by applying to the logbook data the delta model that was developed from the observer data. It is difficult to compare our estimates with those in NBR (NMFS, 2011) and NBR Update 1 because their estimates were species specific, whereas ours were for all species combined. Hata (2006) estimated seabird bycatch during 1986–2005 using the ratio method. Hata (2006)'s estimates were higher than ours for most years (e.g. an estimated annual average of 240 seabirds in 1992 vs. our estimate of 79 seabirds), and had lower precision (e.g. a 95% confidence interval of 48–1209 seabirds for 1992 compared with a CV of 41% in our study for 1992). After considering the variance of the estimates, our estimated values would fall within the 95% confidence interval of the Hata (2006) estimates for most years. By definition, the estimate with the lower CV is more precise, and, based on standards, should be more highly regarded.

Modelling spatial patterns of seabird bycatch

We expected the use of SEM to improve model estimation and prediction by incorporating spatial patterns of seabird bycatch and allowing parameters to vary over space. However, our results for the three areas of highest observed bycatch did not show the superiority of the SEM model over RYEM (Table 4). The larger CVs of SEM estimates may reflect the risk of over-fitting by SEM because of the increased number of parameters that must be used. Two additional parameters would be introduced in SEM for each of the parameters in RYEM, especially when categorical variables are included. For example, both RYEM and global SEM used the categorical variable, target species, in their probability sub-models. Our data involved five target species, and thus the variable, target species, introduced four parameters to estimate in the RYEM whereas it introduced 12 parameters to estimate in the global SEM using the same dataset. Local SEMs may suffer more risk of over-fitting than a global SEM because they have less data to support the estimation of a large number of parameters.

The performance of the localized SEM seems more strongly influenced by the percentage of zero observations in the dataset than the RYEM model and the global SEM. The SAB area had the highest percentage of zero observations (99.5%) and the lowest seabird bycatch, compared with the other two areas and the three areas as a whole (around 98% zero observations; 19–25% CV), and estimates of seabird bycatch in the SAB produced by the localized SEM had the largest CV (65.43%).

In addition to the risk of over-fitting due to potential over-parameterization and the possible sensitivity to the percent of zeros in the database, the SEM may also suffer from the sensitivity of model results to the choice of the expansion function. Fotheringham *et al.* (1998) found that the parameter estimates were different between linear expansion and quadratic expansion. Thus, one should be cautious with the use of the SEM model for estimation and prediction for new locations.

Model evaluation

In this study, we used the CV to evaluate the precision of seabird bycatch estimates from candidate models. The CV goal of 20–30% is suggested by the NMFS's National Bycatch Strategy for fisheries, where bycatch estimation is based on observer data (NMFS, 2004). The Report recognized, however, that this goal might be difficult or impractical to meet because higher observer coverage might be required. The RYEM presented here achieved a CV of 14.72% for its total 21-year estimate of seabird bycatch; however, the CV was above 30% on estimates for individual years (with the exception of 1996, a year with no observed seabird bycatch). The RYEM bycatch estimates had CVs below 20% for the MAB and NEC and below 30% for the SAB and GOM. The CV was a useful criterion for comparing the three types of models examined; the CV differences among model estimates, especially for the seabird bycatch of the SAB, were already noted (Table 4).

In summary, seabird bycatch estimates for areas along the east coast of the United States (e.g. the MAB), and in the seasons of summer, fall and winter were statistically higher than in other areas and in spring. Thus, should management plans be needed to reduce seabird bycatch of United States pelagic longline vessels in the Western North Atlantic, they should focus on these hotspots. Seabirds have been caught less often in the US Atlantic pelagic longline fishery in recent years (e.g. only one seabird caught in each of 2012 and 2013), possibly because the use of J-hook was banned in 2014. Examples of possible management strategies to further reduce seabird bycatch might include increasing fisheries monitoring frequency and coverage in these hotspots, and requiring captains to report bait and hook information (e.g. offset and manufacturer, as well as hook size) in logbooks.

With little spatial variation in the data, the RYEM may be appropriate to estimate seabird bycatch. When spatial patterns appear in the data, the spatial expansion technique could be an alternative, but great caution should be taken due to the risk of over-fitting estimation models. With the advance of computing techniques, we should look to more promising approaches than SEM for addressing spatial non-stationarity that may soon be coming on line.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the article.

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