

# Estimating the risk of loggerhead turtle *Caretta caretta* bycatch in the US mid-Atlantic using fishery-independent and -dependent data

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**ABSTRACT:** The incidental capture, or bycatch, of loggerhead sea turtles *Caretta caretta* in commercial fishing gear is considered a significant threat to their recovery. Bycatch analyses that use fishery-dependent data only reflect the spatial and temporal co-occurrence of turtles and fishing effort and therefore do not directly reveal conditions associated with turtle distributions. Fishery-independent and -dependent data can be used together to identify environmental conditions associated with turtle presence and the subsequent risk of a bycatch encounter if fishing effort is present. We developed generalized additive models (GAMs) to describe fishery-independent encounter rates of loggerheads observed in aerial and resource surveys in the US mid-Atlantic region as a function of environmental variables. We then fit a fishery-independent GAM to fishery-dependent data collected from commercial gillnet, bottom trawl, and scallop dredge fisheries in the mid-Atlantic region, and tested the model on new fishery-dependent data to assess how well the model predicted bycatch events. The preferred model describes fishery-independent encounter rates as a function of latitude, sea-surface temperature, depth, and salinity. When this model was fit to fishery-dependent data and tested on new data, it predicted 85% of the observed bycatch events when grouped by latitude and season, although it underestimated bycatch events in southern latitudes in winter. We identify times and areas of elevated bycatch risk on which to focus future conservation efforts and observer coverage.

**KEY WORDS:** Loggerhead turtle · Bycatch · Fishery-independent data · Fishery-dependent data · Generalized additive model · Northwest Atlantic

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## INTRODUCTION

Protecting a species from threats involves anticipating such threats and avoiding them. As long-lived, late-maturing animals, loggerhead sea turtles *Caretta caretta* are particularly vulnerable to threats such as bycatch in commercial fisheries, which significantly impairs their recovery potential in the Northwest Atlantic (NMFS 2008). Annually, several hundred loggerheads are estimated to be captured incidentally in commercial otter trawl, sink gillnet,

and sea scallop dredge fisheries in US mid-Atlantic waters (from Cape Cod, Massachusetts, to North Carolina, USA) (Murray 2009, 2011, Warden 2011). The majority of loggerheads captured in this region tend to be large juveniles or subadults, though some adults have been observed (Haas 2010, Murray 2011). This region is an important foraging habitat for loggerheads in the Northwest Atlantic Ocean (Musick & Limpus 1997), which comprise a distinct population segment (DPS) listed as threatened under the US Endangered Species Act (ESA).

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Juvenile and subadult loggerheads in the mid-Atlantic have several different migration (McClellan & Read 2007, Mansfield et al. 2009) and foraging (McClellan et al. 2010) strategies, whereby individuals move and feed within neritic and oceanic habitats throughout the year. Typically present in mid-Atlantic waters on a seasonal basis, juvenile and subadult loggerheads migrate to latitudes north of 35° N in the late spring and summer and return south when water temperatures begin to decline (Morreale & Standora 2005, Mansfield et al. 2009). In colder months turtles have migrated as far south as Florida (Mansfield et al. 2009) and have also remained off North Carolina at the edge of the Gulf Stream (Epperly et al. 1995). Characterized as opportunistic feeders (Wallace et al. 2009), loggerheads feed on benthic and pelagic macro-invertebrates (Hopkins-Murphy et al. 2003), and occasionally consume fish (Seney & Musick 2007). Dynamic oceanographic processes presumably influence the distribution of both pelagic and benthic prey, and thus affect where loggerheads forage (Polovina et al. 2006).

A species' migratory and foraging habits are important to understanding and assessing fisheries bycatch, which also threatens other marine megafauna, such as marine mammals, sea birds, and sharks (Lewison et al. 2004). By revealing important environmental features associated with bycatch rates, bycatch models capture mechanisms underlying the co-distribution of the bycatch species and fishing effort. For instance, environmental features have previously been associated with loggerhead bycatch rates in US east coast trawl, dredge, and gillnet fisheries (Murray 2009, 2011, Warden 2011), with sea bird bycatch rates in Alaskan longline fisheries (Dietrich et al. 2009), with pilot whale and Risso's dolphin bycatch rates in US east coast longline fisheries (Garrison 2007), and with Australian fur seal bycatch rates in Australian trawl fisheries (Hamer & Goldsworthy 2006). In general, studies of bycatch only indirectly reveal habitat preferences of bycatch species because sampling typically occurs where commercial vessels fish. Moreover, bycatch analyses are usually focused on a single fishing gear, making it difficult to assess broader associations between environmental features and the potential for bycatch (Wallace et al. 2010).

Risk assessments of fisheries interactions with protected species are often evaluated by overlaying fishing effort with static maps of animal distributions derived from fishery-independent data (McDaniel et al. 2000, Grech et al. 2008, Sonntag et al. 2012). The integration of dynamic habitat models with fishing effort data has helped advance these types of assess-

ments because the models capture the underlying oceanographic mechanisms influencing interactions with mobile species (Zydelis et al. 2011). They can also be used to reduce the spatio-temporal overlap between fishing effort and the bycatch species. For example, temperature-based habitat models for southern bluefin tuna in Australia have been used to design management zones which control access to fishers (Hobday & Hartmann 2006); a similar system has been designed for loggerhead turtles in Hawaiian longline fisheries (Howell et al. 2008). However, data to inform habitat models, such as those obtained from surveys or tagged animals, may be difficult to obtain long-term over large areas; moreover, telemetry data provide just presence-only information, requiring the need to simulate pseudo-absence locations (Zydelis et al. 2011).

Fishery-independent and -dependent data can be used together to estimate the risk of protected species bycatch. There are other areas of the world where protected species habitat models have been developed from fishery-independent data (Gilles et al. 2011, Forney et al. 2012), and focus on regions where a diverse fishing industry is sampled via a fisheries observer program. These habitat models can inform *a priori* models of protected species bycatch, to help capture the mechanisms underlying the co-distribution of protected species and fishing effort. Projecting a landscape of risk from these models can help inform discussions regarding times and areas to focus bycatch mitigation, or consequences to protected species of fishery management actions.

In the present study, we used both fishery-independent and -dependent data to estimate the risk of protected species bycatch. We examined environmental conditions associated with encounter rates of loggerhead turtles observed using fishery-independent platforms, and then evaluated whether loggerhead bycatch events could be predicted under similar environmental conditions. Our objectives were to: (1) use fishery-independent data to construct models that described loggerhead encounter rates as a function of environmental variables; (2) fit a preferred model from the fishery-independent data to fishery-dependent data collected from 4 different commercial gear types; and (3) test the model on new fishery-dependent data to assess retrospectively how well the model predicted bycatch events, both temporally and spatially. We expected that our modeling results would identify times, areas, and environmental conditions in the mid-Atlantic which result in elevated risks of loggerhead interactions with commercial fishing gear.

## MATERIALS AND METHODS

Our analysis of loggerhead *Caretta caretta* encounter rates was based on data collected from the continental shelf of waters of southern New England and the mid-Atlantic, conforming roughly to an area from 42 to 34°N, from the shore to roughly the 200 m depth contour (Fig. 1). As further described below, we modeled 3 different types of encounter rates from 3 sampling platforms. We were interested in identifying relative patterns in encounter rates in the mid-Atlantic, versus quantifying absolute rates, because we recognize that factors influencing encounter rates from these platforms may differ. After identifying and accounting for the environmental factors that affect encounter rates, we assume that other factors influencing encounter rates are independent and do not influence the modeled encounter rates.

## Data sources

### Fishery-independent data

We used data collected by observers on aerial line transect abundance surveys conducted from June through August in 1995, 1998, 2004, and 2006 (Palka 2006). The surveys covered waters from roughly 42 to 36°N, from the coastline to roughly the 200 m depth contour. We divided each survey track line into segments ranging from 9 to 17 km, where the average length was 12 km and sighting conditions (Beaufort sea state and observers) within a segment were consistent. The aerial dataset comprised 1099 segments and 421 loggerheads. Transect segments were consistent with average distances traveled for a mobile fishing gear haul in the fishery-dependent data set described below. Encounter rates were defined as the number of loggerhead sightings per

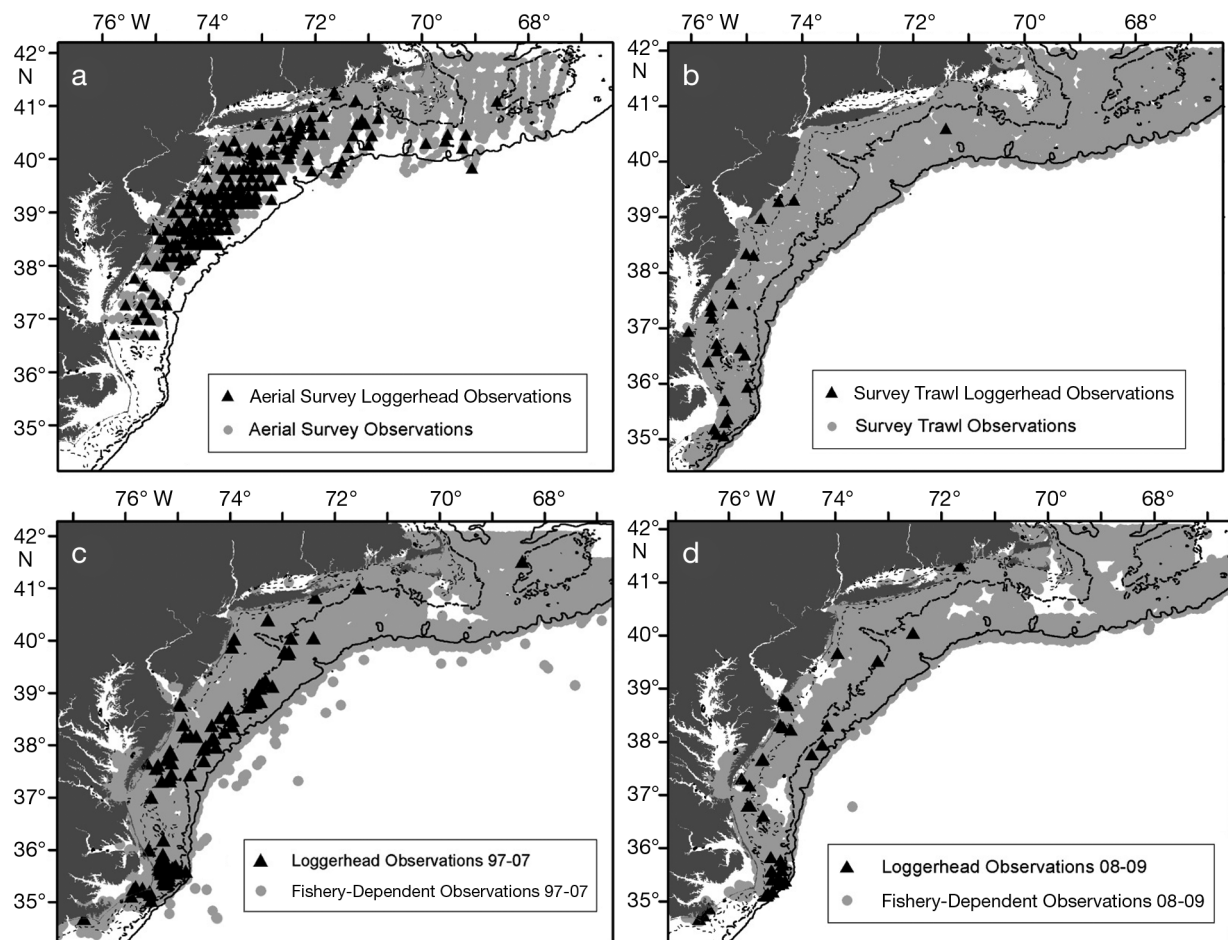


Fig. 1. *Caretta caretta*. Distribution of fishery-independent and -dependent observations used in the present study. The 20, 50, and 200 m bathymetry lines are also shown. (a) Aerial survey observations, (b) resource survey trawl observations, (c) fishery-dependent observations from 1997 to 2007, and (d) fishery-dependent observations from 2008 to 2009

time-distance (h-km), where time-distance equaled the length of the transect segment multiplied by the flight duration of that segment (0.04 to 0.08 h).

We also used data collected from Northeast Fisheries Science Center (NEFSC) bottom trawl resource surveys ( $n = 5487$  observations, 23 loggerheads), collected annually from February to May and September to November from 1997 to 2008. These surveys are designed to provide information on the abundance, biology, and distribution of the living marine resources of the Northwest Atlantic. At each sampling station in these surveys, the trawl net is towed for 0.5 h at an average speed of 3.5 knots. Time-distance on each haul was computed as the time spent towing (h) multiplied by the distance traveled (km).

#### Fishery-dependent data

To derive loggerhead encounter rates (expressed as the number of observed loggerheads per time-distance), we used data collected from 1997 to 2007 by NEFSC observers deployed aboard commercial vessels fishing with bottom otter trawls (40 % of observations), sink gillnets (25 %), sea scallop dredges (34 %), and sea scallop trawls (1 %). The sampling unit was a haul. For mobile gears (trawls and dredges), time-distance on each haul was computed as time spent fishing multiplied by the distance traveled. For passive gear (sink gillnets), where a series of net panels are assembled together in a string that rests on the ocean bottom, time-distance was computed as soak time of the nets (h) multiplied by the total length of the string (km). The observer data were collected year-round, and included 142 000 hauls and 125 observed loggerhead captures (Fig. 1b). Of the 125 incidentally captured turtles, 66 were taken in otter trawls, 26 in dredges, and 33 in sink gillnets. The model fit to these data was tested on new fishery-dependent data, inclusive of the same gear types, collected year-round in 2008 and 2009. The 2008 to 2009 dataset comprised 69 000 hauls and 52 observed loggerhead captures (Fig. 1c).

#### Environmental variables

We obtained environmental variables from the beginning of each aerial survey transect piece, or at the start of each fishing haul. If point values were unavailable, we obtained values from within a 13.75 km<sup>2</sup> area around the point position to be within the length of a survey transect piece or average dis-

tance traveled over a haul. We obtained surface salinity (parts per thousands) from either the real time ocean forecast system (RTOFS) model (May 2006 to present) (Mehra & Rivin 2010) or the regional ocean forecast system (ROFS) model (pre-May 2006) (Breaker et al. 2004), using a tool developed at the NEFSC (Brick Builder, Version 1.0). We obtained surface salinity for each haul or transect start location from the nearest ocean model grid point, up to 14 km<sup>2</sup> from the point location.

We obtained chlorophyll data (mg m<sup>-3</sup>) from 5 d composites of SeaWiFS high resolution satellite images (<http://oceancolor.gsfc.nasa.gov>) from 1997 to 2007. We retrieved chlorophyll values at point locations, or from median values for the surrounding area (13.75 km<sup>2</sup>), and then log-transformed these values (Yoder et al. 2001) to model the data.

We used sea-surface temperature (SST) (°C) from 2 sources: (1) blended NEFSC SST data from AVHRR Pathfinder, Modis Aqua, Modis Terra, and GOES satellites to create overlapping 5 d SST composites for each day from 1997 through 2007, or, alternatively, (2) non-overlapping 5 d climatology images, one for each consecutive 5 d period during the year (Armstrong & Vazquez-Cuervo 2001). We used data from point locations when available for the final SST value; otherwise, we used median values for the surrounding area (13.75 km<sup>2</sup>).

We used observer-recorded depth (m) values when available. When these data were missing, we obtained depth values at a given geographic location from the following sources in decreasing frequency: (1) Coastal Relief data<sup>1</sup>, (2) Shuttle Radar Topography Mission 30 Version 3 data<sup>2</sup> (Smith & Sandwell 1997, Becker et al. 2009), or (3) National Geophysical Data Center ETOPO5 data<sup>3</sup>. Several sources of depth data were needed to obtain values for the entire study area.

#### Model building with fishery-independent data

Using just the fishery-independent data, we considered 2 approaches to model the expected loggerhead encounter rate, where the encounter rate was expressed as the number of observed loggerheads

<sup>1</sup>NOAA National Geophysical Data Center, U.S. Coastal Relief Model, August 27, 2007, [www.ngdc.noaa.gov/mgg/coastal/crm.html](http://www.ngdc.noaa.gov/mgg/coastal/crm.html)

<sup>2</sup>[http://topex.ucsd.edu/WWW\\_html/srtm30\\_plus.html](http://topex.ucsd.edu/WWW_html/srtm30_plus.html)

<sup>3</sup>NOAA National Geophysical Data Center, ETOPO5, June 1, 2004, [www.ngdc.noaa.gov/mgg/global/etop5.html](http://www.ngdc.noaa.gov/mgg/global/etop5.html)

per time-distance. First, we explored the zero-inflated Poisson (ZIP) mixture model (`zeroinfl` function, R 2.1), a modification to the usual Poisson distribution to account for extra zeros in the data (Lambert 1992). The ZIP model is a mixture of logistic and Poisson regression models, where the probability of a loggerhead occurrence at a given site is modeled with a logistic function, and the loggerhead density at a given site, given the probability of occurrence, is modeled with a Poisson function. Mixture models are appropriate when the zero-inflation is due to both true zeros, i.e. a species does not occur at a site because of unsuitable habitat, and to false zeros, i.e. a species could occur but was not present during the survey period, or was present but the observer failed to detect it (Martin et al. 2005). We found the ZIP model to be difficult to interpret ecologically, with regard to important covariates and predicted values. For instance, the significance and directionality of the parameter estimates (+/−) for one variable might change depending on which component of the mixture model was being explained. As this issue has also been raised in other studies (Welsh et al. 1996), we decided to model encounter rates with a generalized additive model (GAM), appropriate for non-linear data structures when describing ecological systems (Guisan et al. 2002).

We used a GAM with a Poisson distribution (GAM function, `SPLUS 7.0`) to model the expected loggerhead encounter rate, where the encounter rate was expressed as the number of observed loggerheads per time-distance. The form of the GAM can be written as:

$$\text{Log}(E[y_j]) = \log(\text{time-dist}_j) + \alpha + \sum_{i=1}^n f_i(x_{ij}) + \xi \quad (1)$$

where  $y_j$  is the number of loggerheads observed on the  $j$ th transect or haul,  $\log(\text{time-dist}_j)$  is an offset term for the unit of effort (time-distance) on the  $j$ th transect or haul (in h-km),  $\alpha$  is a constant intercept term,  $f_i$  are a series of smoothing splines for each predictor variable,  $x_{ij}$  are environmental characteristics at the beginning of each transect or haul, and  $\xi$  is unexplained error (Hastie & Tibshirani 1990).

Candidate variables for model building included: SST, depth, latitude, chlorophyll, and surface salinity. We excluded other variables from model testing (distance to a chlorophyll front, distance to a sea surface front, sea surface and chlorophyll frontal intensities, month, longitude) if >10% of the data had to be imputed, were beyond the 13.75 km<sup>2</sup> spatial window, or were correlated (>0.6 from a Spearman's rank correlation analysis) with a candidate variable. We

chose the primary candidate variables based on *a priori* knowledge of factors affecting loggerhead distribution or loggerhead bycatch rates. SST, depth, and latitude have previously been associated with loggerhead bycatch rates (Murray 2009, Warden 2011); these variables also capture the spatial and temporal variation in loggerhead distributions during their seasonal migrations (Mansfield et al. 2009, Hawkes et al. 2011). We defined seasons based on Warden (2011), which were based on warming and cooling patterns in the mid-Atlantic tied to loggerhead distributions (Braun-McNeill et al. 2008). These were: winter (1 December to 15 April), spring (16 April to 15 May), summer (16 May to 31 October), and fall (1 to 30 November). Chlorophyll gradients, caused by wind mixing and Gulf Stream interactions in shelf/slope frontal regions in the mid-Atlantic (Yoder et al. 2001), are associated with foraging behavior of loggerheads in both the Atlantic (McCarthy et al. 2010) and the Pacific (Polovina et al. 2004). Seasonal changes in temperature and the salinity in the central mid-Atlantic control water stratification (Castelao et al. 2010), which influences both circulation patterns and nutrient levels in the water column.

We developed separate models for the aerial survey dataset and for the survey trawl dataset because encounter rates from these 2 sources are not directly comparable, and the probability of encountering a loggerhead of any size differs between the 2 survey platforms. Because the fishery-independent data were collected in different seasons, we developed 2 different seasonal models from the fishery-independent data: a mid-summer model (from aerial survey observations) and a late summer, winter/early spring model (from survey trawl observations).

For each dataset, we tested the primary variables in a forward stepwise model selection process (step.gam function, `SPLUS 7.0`). The null model—consisting of the overall mean—was the initial model in the stepwise procedure. At each step, the forward stepwise algorithm selected the variable that generated the greatest change in the Akaike information criterion (AIC) (Akaike 1973, Burnham & Anderson 2002) relative to all other model variables. Continuous variables were considered as smooth terms in the model using the default degrees of freedom in the fitting procedure. To ensure the step.gam procedure did not overfit, we manually added variables to the null model in the same order in which the automated procedure selected the variables, and then evaluated the amount of deviance reduced. We excluded variables that reduced deviance by <2% (Maunder & Punt 2004).



### Model performance on fishery-dependent data

Next we modeled fishery-dependent encounter rates from 1997 to 2007 as a function of the same environmental variables from the 2 fishery-independent models, and evaluated them with respect to AIC. Thus, we did not force the same functional relationships from each of the fishery-independent models to the fishery-dependent data. The fishery-dependent model we selected as the preferred model had a lower AIC and included all the variables contained in the alternative seasonal model. After choosing the preferred model, we tested year and season as secondary variables to determine if these variables explained significantly more variation in encounter rates than that already explained. We also examined the preferred model for overdispersion, measured by calculating the dispersion parameter ( $\Phi$ ), defined as:

$$\Phi = \frac{\sum (y_i - \hat{\mu}_i)^2 / \hat{\mu}_i}{\text{residual df}} \quad (2)$$

Finally, we tested the preferred model on new fishery-dependent data from 2008 and 2009 and evaluated errors (defined as predicted loggerhead – observed loggerhead) with respect to latitude (binned into 1° blocks) and season strata. In predicting observed bycatch in new years, we assumed that the magnitude and distribution of observer coverage was constant over time.

## RESULTS

### Model building with fishery-independent data

The preferred variables for explaining variation in loggerhead *Caretta caretta* encounter rates in the aerial survey data (the summer model) were latitude and SST, whereas in the bottom otter trawl survey data (the winter/early spring model) the preferred variables were latitude, SST, depth, and salinity (Table 1a,b). The bottom trawl survey model was selected as the preferred model for describing loggerhead encounter rates because it had a lower AIC than the aerial survey model and was inclusive of the aerial survey model variables (Table 1c, Fig. 2a).

### Model performance on fishery-dependent data

The preferred model fitted to the fishery-dependent data from 1997 to 2007 described 38% of the model deviance (Table 1c). Year and season explained <1% additional variance over these variables. The estimated dispersion value of the preferred model was 0.86, indicating no overdispersion. Plots of the smoothed model terms indicated a decreasing trend in encounter rates as latitude increases, an increasing trend as SST increases, a bimodal relationship between encounter rates and salinity, and

Table 1. *Caretta caretta*. Results from the (a) aerial and (b) bottom otter trawl survey data step-wise models. Rows in bold indicate the preferred model. Variables that explained <2% additional deviance were not retained in the model. (c) Seasonal models from fishery-independent data fit to fishery-dependent data. AIC: Akaike information criterion; s: smoothed

Model No.	Model structure	Approx. df	Cumulative percent deviance explained	Increase in percent deviance explained	AIC
<b>(a) Aerial survey</b>					
1	Null	1			1784.3
2	s(latitude)	4.0	38.9		1097.5
<b>3</b>	<b>s(latitude) + s(depth)</b>	<b>6.9</b>	<b>44.2</b>	<b>5.3</b>	<b>1012.8</b>
4	s(latitude) + s(depth) + s(salinity)	9.9	46.0	1.8	988.6
5	s(latitude) + s(depth) + s(chlorophyll)	9.9	45.9	1.7	990.0
6	s(latitude) + s(depth) + s(SST)	9.8	45.3	1.1	999.7
<b>(b) Bottom otter trawl</b>					
1	Null	1			260.0
2	s(latitude)	4.0	14.5		230.5
3	s(latitude) + s(SST)	6.9	24.8	10.3	211.7
4	s(latitude) + s(SST) + s(depth)	9.9	31.8	7.0	201.3
<b>5</b>	<b>s(latitude) + s(SST) + s(depth) + s(salinity)</b>	<b>12.7</b>	<b>35.7</b>	<b>3.9</b>	<b>199.0</b>
6	s(latitude) + s(SST) + s(depth) + s(salinity) + season	15.7	35.8	0.1	204.7
5	s(latitude) + s(SST) + s(depth) + s(salinity) + s(chlorophyll)	15.7	36.4	0.7	205.0
<b>(c) Independent data fit to dependent data</b>					
Model structure	Approx. df	Percent deviance explained		AIC	
s(latitude) + s(depth)	6.9	29.2		1378.3	
s(latitude) + s(SST) + s(depth) + s(salinity)	12.6	38.1		1223.2	

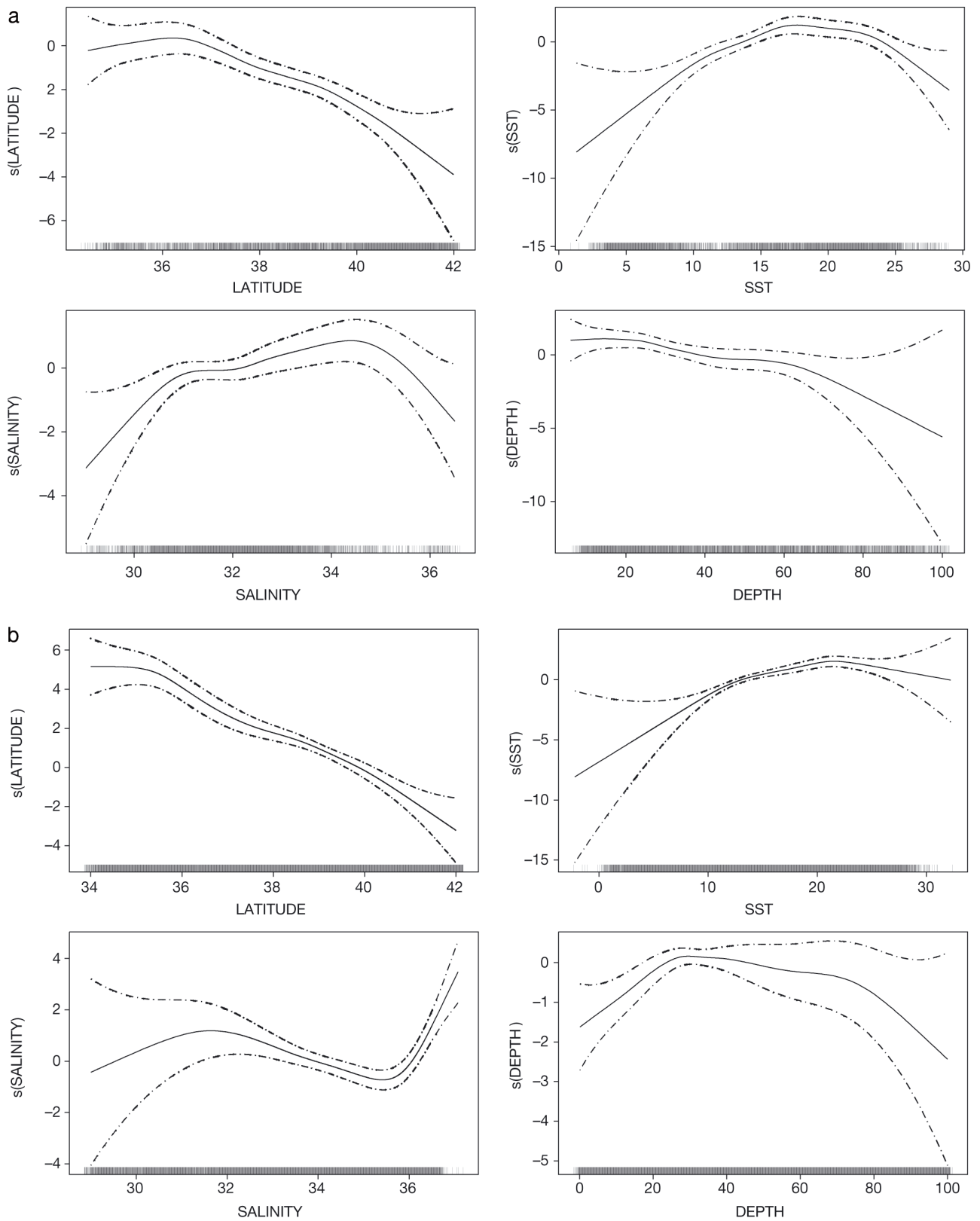


Fig. 2. *Caretta caretta*. Generalized additive model smoothers depicting the effect of covariates on estimated encounter rates in (a) fishery-independent, bottom otter trawl survey data and (b) fishery-dependent data. SST: sea surface temperature

higher encounter rates in water depths between 25 and 50 m (Fig. 2b).

When this model was applied to new fishery-dependent data in 2008 and 2009, the model predicted a bycatch of 44 loggerheads compared to 52 observed. Predictions were best in summer, and underestimated around 35°N in winter (Table 2). Higher encounter rates were estimated year-round in southern latitudes, and in mid-shelf areas between 37 and 40°N from mid-May through October (Fig. 3).

## DISCUSSION

This is the first comprehensive examination of loggerhead *Caretta caretta* encounter rates in the mid-Atlantic and southern New England using both fishery-independent and -dependent data, spanning multiple gear types and data collection platforms. Results suggest that encounter rates modeled with fishery-independent data are associated with latitude, SST, salinity, and depth, and these covariates also explain variation in encounter rates documented via fishery-dependent data. The associations with most of these environmental factors are consistent with previous loggerhead bycatch analyses (Murray 2009, 2011, Warden 2011, Warden & Murray 2011). After the preferred model was fit to the fishery-dependent data, year and season explained very little additional variation in encounter rates in the model, suggesting that the variables chosen for the model capture both inter- and intra-annual variability in loggerhead encounter rates.

As depicted by the GAM smoothers, the effect of latitude, SST, depth, and salinity on estimated encounter rates followed similar trends in the survey

trawl data (which led to the preferred model) and in the fishery-dependent data. The exception was salinity, which exhibited opposite trends beyond 32 ppt. The association between encounter rates and salinity may reflect a seasonal response by loggerheads and fishing effort to water stratification and shelf circulation dynamics in the central and southern mid-Atlantic. Differences in salinity smoothers may reflect the time period during which the fishery-independent and -dependent data were collected, as well as the pattern of observed encounters in the 2008 and 2009 test dataset. The fishery-independent survey model reflected salinity levels from winter and early spring, versus the fishery-dependent data, which reflected salinity levels year-round. Furthermore, in the summer of 2009, there were several loggerheads observed inside the North Carolina barrier islands, a time and area of high salinity.

The fishery-dependent model estimated high encounter rates year-round south of 37°N and in mid-shelf waters to the north from mid-May to October. This pattern generally aligns with the seasonal migration of loggerheads into and out of the mid-Atlantic (Mansfield et al. 2009, Hawkes et al. 2011). The region south of 37°N is an area of high loggerhead use (TEWG 2009) and high estimated bycatch rates (Epperly et al. 1995, Murray 2009, Warden 2011). Here waters of the mid-Atlantic and South Atlantic converge, impacting the physical oceanography of this area (Flagg et al. 2002, Lohrenz et al. 2002). The shelf-slope front, a characteristic of the mid-Atlantic that strongly influences circulation dynamics, is absent close to the North Carolina barrier islands because the Gulf Stream runs very close to the 200 m shelf break (Yoder et al. 2001, Townsend et al. 2006). The narrowness of the shelf and the influence of the

Table 2. *Caretta caretta*. Observed (O) versus predicted (P) number of loggerheads incidentally captured in commercial gillnet, dredge, and trawl gears when model applied to new fishery-dependent data. A = average squared prediction error, computed as  $(O - P)^2/n$ , where  $n$  is the total number of observations in that latitude/season block

Latitude (°N)	Winter (1 Dec–15 Apr)			Spring (16 Apr–15 May)			Summer (16 May–31 Oct)			Fall (1–30 Nov)		
	O	P	A	O	P	A	O	P	A	O	P	A
33	0	0.02	<0.001	0	0.03	<0.001	0	0.05	<0.001	0	0.09	<0.001
34	0	0.16	<0.001	0	0.00	<0.001	3	0.84	0.019	0	0.04	<0.001
35	19	2.68	0.165	0	0.15	<0.001	0	0.76	<0.001	5	2.23	0.064
36	0	1.53	<0.001	0	0.10	<0.001	3	1.25	0.027	0	0.39	<0.001
37	0	0.68	<0.001	0	0.40	<0.001	6	2.58	0.006	0	0.34	<0.001
38	0	1.64	<0.001	0	1.16	<0.001	12	12.10	0.003	0	3.48	<0.001
39	0	0.17	<0.001	0	0.46	<0.001	2	5.87	<0.001	0	0.10	<0.001
40	0	0.07	<0.001	0	0.09	<0.001	1	2.84	<0.001	0	0.04	<0.001
41	0	0.01	<0.001	0	0.01	<0.001	1	1.12	<0.001	0	0.06	<0.001
Total	19	6.96	0.002	0	2.40	<0.001	28	27.41	<0.001	5	6.77	0.001



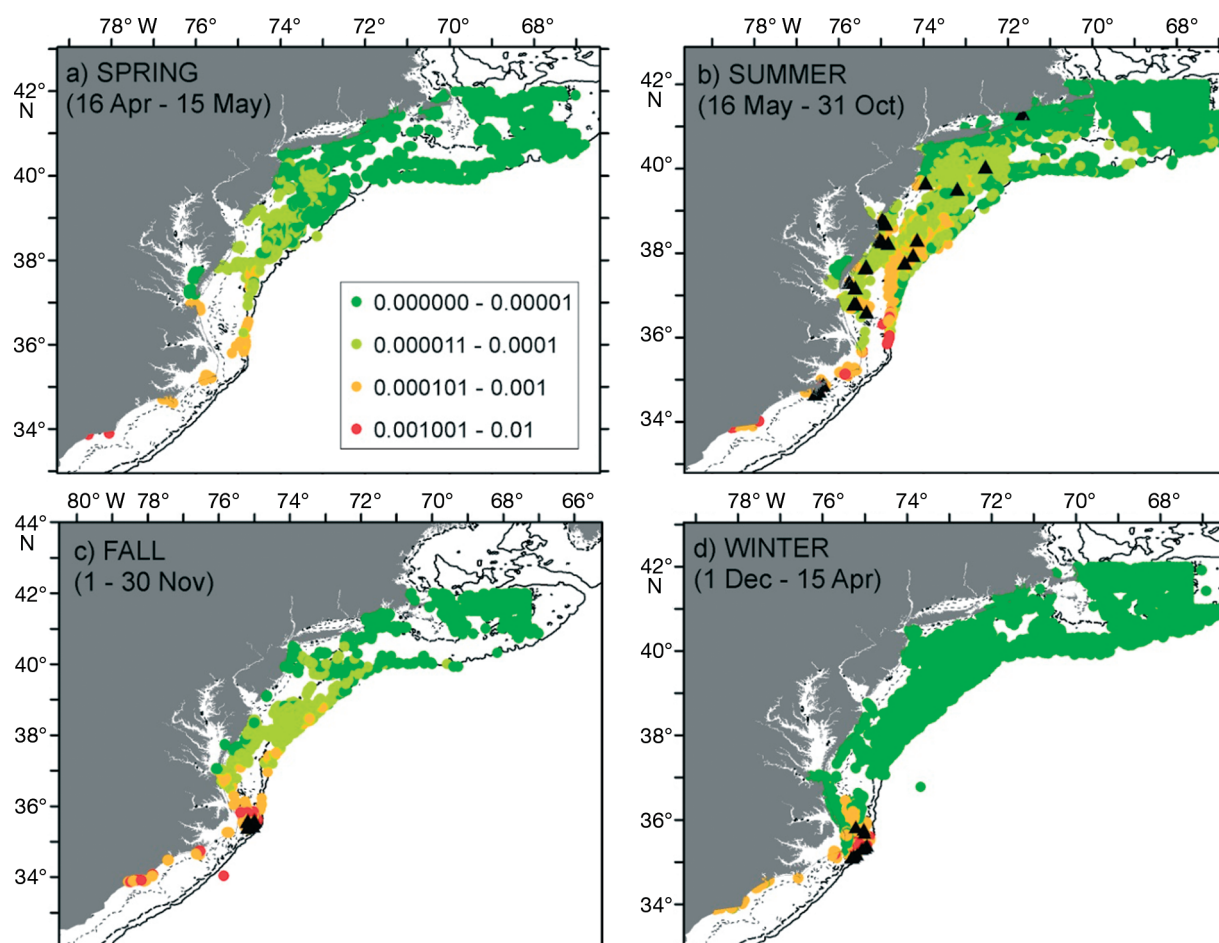


Fig. 3. *Caretta caretta*. (a–d) Estimated loggerhead encounter rates by season in 2008 to 2009 fishery-dependent data. Black triangles represent observed loggerheads. The 20, 50, and 200 m bathymetry contours are also shown

Gulf Stream around Cape Hatteras increase salinity in this region relative to areas farther north and concentrate turtles emigrating from the mid-Atlantic, putting the turtles at greater risk of possible interactions with fishing activity (Epperly et al. 1995).

By identifying times and areas with elevated risk of bycatch, this study can help focus bycatch reduction efforts and observer coverage. Waters south of 37°N, to the southern extent of this analysis, have an elevated potential for loggerhead bycatch events year-round, as do waters between 37 and ~40°N during the period from May to October. This pattern is generally consistent across different gear types (trawl, gillnet, and dredge) operating in the area. We informally tested gear type as a variable to explain differences in estimated encounter rates in the fishery-dependent model and found that it explained about 5% of model deviance. Due to major differences in gillnet fishing practices after 2007, as well as gear modifications in the dredge fishery, we could not include gear type in the model tested on new data in

2008 to 2009. Although gear type explained only a small amount of variance in the model, it does suggest that within a time and area with elevated risk of bycatch, attention could be given to specific gear types (and how they are fished).

Model predictions in this region were most accurate in spring and fall and poorest in the winter. Poor predictions in the winter could be due to a modeling effect, or to a lack of fishery-independent data in this region. The GAM may not adequately capture potential interaction effects between SST and latitude (e.g. encounters with turtles in cool water temperatures could happen off North Carolina, but not at the same SST farther north, due to the seasonal distribution of the animals) or clustered events (e.g. the GAM estimated <1 turtle on 2 hauls in each of which 4 turtles were captured). Additionally, specific fishery-independent data in this region would be helpful to capture the influence of oceanographic processes on loggerhead encounter rates off North Carolina; this includes the need for data from December and Janu-

ary and the expansion of aerial survey data outside the central part of the mid-Atlantic during summer.

The techniques used here to examine the risk of fisheries interactions with protected species could be applied to other regions where overlap exists between fisheries-dependent and -independent data. For instance, cetaceans, sea birds, and turtles are captured incidentally in trawl and gillnet fisheries off the US west coast (Julian & Beeson 1998, Jannot et al. 2011), as documented by fisheries observers. Data from ship-board surveys in the California Current ecosystem have been used to model encounter rates and density of cetacean species in the same general area occupied by some of these fisheries (Forney et al. 2012); average encounter rates over several years were modeled as a function of environmental conditions such as depth, SST, mixed-layer depth, and chlorophyll. By explaining persistent conditions influencing the distribution of mobile animals, these models can help guide the development of models to predict interactions using fisheries observer data. Identifying these bycatch 'hotspots' can help managers evaluate mitigation tools, such as shifts or reductions in fishing effort (Howell et al. 2008).

One issue to consider when replicating the approach used in the present study is the appropriate scale at which to model the data. The outcome of a habitat model will likely depend on the scale of the variables examined (Wiens 1989). We obtained environmental data from a 13.75 km<sup>2</sup> area around the point location, within a 5 d window of the point location. The spatial choice was based mainly around the average distance traveled for mobile fishing gear, so that all samples reflected conditions from a similar-sized environmental window; the temporal choice helped minimize missing data due to cloud cover. However, the effect of oceanographic processes on turtle distribution may vary over different temporal and spatial scales depending on their behavior; for instance, foraging turtles may exploit local food patches within small spatial scales (Arendt et al. 2012), while migrating turtles may be responding to environmental cues over larger areas and time frames (Mansfield et al. 2009).

The spatial scale of the analysis may also influence the availability and quality of the data used for model development. In the present study, values of some environmental variables obtained from remote sources (i.e. distance to an SST or chlorophyll front, frontal intensities) were either missing or too far away from the point location. If these were >10% of the data, we dropped the variable from the model selection process rather than eliminate the observa-

tions so as not to lose any loggerhead events. Dropping these candidate variables limited our analysis of oceanographic predictors. If we had been modeling at a larger spatial scale we may have been able to average values within a larger spatial window, eliminating the need to drop missing data. Future analyses might investigate the predictive ability of alternative temporal and spatial scales on interaction rates, as has been done in other studies (Becker et al. 2010).

In summary, the present study helps identify times and areas with heightened estimated risk of loggerhead encounters in commercial fishing gears. This information may help design bycatch reduction efforts, such as evaluations of potential effects of seasonal closures, and focus fisheries observer sampling when resources are limited. However, further work is needed to develop models of loggerhead habitat and to predict the distribution of fishing effort. Furthermore, better tools are needed to accurately forecast oceanographic conditions in the mid-Atlantic (Hobday et al. 2011). When these 3 advancements converge, we will have made great headway in reducing loggerhead bycatch.

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#### LITERATURE CITED

- Akaike H (1973) Information theory as an extension of the maximum likelihood principle. In: Petrov B, Csaki F (eds) Second international symposium on information theory. Akademiai Kiado, Budapest, p 267–281
- Arendt M, Boynton J, Schwenter J, Byrd J and others (2012) Spatial clustering of loggerhead sea turtles in coastal waters of the NW Atlantic Ocean: implications for management surveys. *Endang Species Res* 18:219–231
- Armstrong EM, Vazquez-Cuervo J (2001) A new global satellite-based sea surface temperature climatology. *Geophys Res Lett* 28:4199–4202
- Becker JJ, Sandwell DT, Smith WHF, Braud J and others (2009) Global bathymetry and elevation data at 30 arc seconds resolution: Srtm30\_plus. *Mar Geod* 32:355–371
- Becker EA, Forney KA, Ferguson MC, Foley DG, Smith RC, Barlow J, Redfern JV (2010) Comparing California Current cetacean-habitat models developed using *in situ* and remotely sensed sea surface temperature data. *Mar Ecol Prog Ser* 413:163–183
- Braun-McNeill J, Sasso CR, Epperly SP, Rivero C (2008) Feasibility of using sea surface temperature imagery to mitigate cheloniid sea turtle–fishery interactions off the

- coast of northeastern USA. *Endang Species Res* 5: 257–266
- Breaker LC, Rao DB, Kelly JGW, Rivin I, Balasubramaniyam B (2004) Development of a real-time regional ocean forecast system with application to a domain off the US east coast. *Mar Technol Soc J* 38:61–79
- Burnham K, Anderson D (2002) Model selection and multi-model inference, 2nd edn. Springer, New York, NY
- Castelao R, Glenn S, Schofield O (2010) Temperature, salinity, and density variability in central middle Atlantic bight. *J Geophys Res* 115:1–14
- Dietrich KS, Parrish JK, Melvin EF (2009) Understanding and addressing seabird bycatch in Alaska demersal longline fisheries. *Biol Conserv* 142:2642–2656
- Epperly SP, Braun J, Chester AJ, Cross FA, Merriner JV, Tester PA (1995) Winter distribution of sea turtles in the vicinity of Cape Hatteras and their interactions with the summer flounder trawl fishery. *Bull Mar Sci* 56:547–568
- Flagg CN, Pietrafesa LJ, Weatherly GL (2002) Springtime hydrography of the southern middle Atlantic bight and the onset of seasonal stratification. *Deep-Sea Res II* 49: 4297–4329
- Forney KA, Ferguson MC, Becker EA, Fiedler PC and others (2012) Habitat-based spatial models of cetacean density in the eastern Pacific Ocean. *Endang Species Res* 16: 113–133
- Garrison LP (2007) Interactions between marine mammals and pelagic longline fishing gear in the U.S. Atlantic Ocean between 1992 and 2004. *Fish Bull* 105:408–417
- Gilles A, Adler S, Kaschner K, Scheidat M, Siebert U (2011) Modelling harbour porpoise seasonal density as a function of the German bight environment: implications for management. *Endang Species Res* 14:157–169
- Grech A, Marsh H, Coles R (2008) A spatial assessment of the risk to a mobile marine mammal from bycatch. *Aquat Conserv* 18:1127–1139
- Guisan A, Edwards TC Jr, Hastie T (2002) Generalized linear and generalized additive models in studies of species distributions: setting the scene. *Ecol Modell* 157:89–100
- Haas H (2010) Using observed interactions between sea turtles and commercial bottom-trawling vessels to evaluate the conservation value of trawl gear modifications. *Mar Coast Fish Dynam Manag Ecosyst Sci* 2:263–276
- Hamer DJ, Goldsworthy SD (2006) Seal-fishery operational interactions: identifying the environmental and operational aspects of a trawl fishery that contribute to bycatch and mortality of Australian fur seals (*Arctocephalus pusillus doriferus*). *Biol Conserv* 130:517–529
- Hastie TJ, Tibshirani RJ (1990) Generalized additive models. Chapman & Hall, New York, NY
- Hawkes LA, Witt MJ, Broderick AC, Coker JW and others (2011) Home on the range: spatial ecology of loggerhead turtles in Atlantic waters of the USA. *Divers Distrib* 17: 624–640
- Hobday AJ, Hartmann K (2006) Near real-time spatial management based on habitat predictions for a longline bycatch species. *Fish Manag Ecol* 13:365–380
- Hobday AJ, Hartog JR, Spillman CM, Alves O (2011) Seasonal forecasting of tuna habitat for dynamic spatial management. *Can J Fish Aquat Sci* 68:898–911
- Hopkins-Murphy S, Owens DW, Murphy TM (2003) Ecology of immature loggerheads on foraging grounds and adults in interbreeding habitat in the eastern United States. In: Bolten AB, Witherington BE (eds) *Loggerhead sea turtles*. Smithsonian Institution Press, Washington, DC, p 79–92
- Howell EA, Kobayashi DR, Parker DM, Balazs GH, Polovina JJ (2008) Turtlewatch: a tool to aid in the bycatch reduction of loggerhead turtles (*Caretta caretta*) in the Hawaii-based longline fishery. *Endang Species Res* 5:267–278
- Jannot J, Heery E, Bellman MA, Majewski J (2011) Estimated bycatch of marine mammals, seabirds, and sea turtles in the US west coast commercial groundfish fishery, 2002–2009. National Marine Fisheries Service, NWFS, West Coast Groundfish Observer Program, Seattle, WA
- Julian F, Beeson M (1998) Estimates of marine mammal, turtle, and seabird mortality for two California gillnet fisheries: 1990–1995. *Fish Bull* 96:271–284
- Lambert D (1992) Zero-inflated Poisson regression, with an application to the defects in manufacturing. *Technometrics* 34:1–14
- Lewison RL, Crowder LB, Read AJ, Freeman SA (2004) Understanding impacts of fisheries bycatch on marine megafauna. *Trends Ecol Evol* 19:598–604
- Lohrenz SE, Redalje DG, Verity PG, Flagg CN, Matulewski KV (2002) Primary production on the continental shelf off Cape Hatteras, North Carolina. *Deep-Sea Res II* 49: 4479–4509
- Mansfield KL, Saba VS, Keinath JA, Musick JA (2009) Satellite tracking reveals dichotomy in migration strategies among juvenile loggerhead turtles in the Northwest Atlantic. *Mar Biol* 156:2555–2570
- Martin TG, Wintle BA, Rhodes JR, Kuhnert PM and others (2005) Zero tolerance ecology: improving ecological inference by modelling the source of zero observations. *Ecol Lett* 8:1235–1246
- Maulander MN, Punt AE (2004) Standardizing catch and effort data: a review of recent approaches. *Fish Res* 70: 141–159
- McCarthy AL, Heppell S, Royer F, Freitas C, Dellinger T (2010) Identification of likely foraging habitat of pelagic loggerhead sea turtles (*Caretta caretta*) in the North Atlantic through analysis of telemetry track sinuosity. *Prog Oceanogr* 86:224–231
- McClellan CM, Read AJ (2007) Complexity and variation in loggerhead sea turtle life history. *Biol Lett* 3:592–594
- McClellan CM, Braun-McNeill J, Avens L, Wallace BP, Read AJ (2010) Stable isotopes confirm a foraging dichotomy in juvenile loggerhead sea turtles. *J Exp Mar Biol Ecol* 387:44–51
- McDaniel CJ, Crowder LB, Priddy JA (2000) Spatial dynamics of sea turtle abundance and foraging intensity in the U.S. Gulf of Mexico. *Conserv Ecol* 4(1):15, available at [www.consecol.org/vol4/iss1/art15/](http://www.consecol.org/vol4/iss1/art15/)
- Mehra A, Rivin I (2010) A real time ocean forecast system for the North Atlantic Ocean. *Terrestrial Atmos Ocean Sci* 21:211–228
- Morreale S, Standora E (2005) Western North Atlantic waters: crucial developmental habitat for Kemp's ridley and loggerhead sea turtles. *Chelonian Conserv Bio* 4: 872–882
- Murray KT (2009) Characteristics and magnitude of sea turtle bycatch in US mid-Atlantic gillnet gear. *Endang Species Res* 8:211–224
- Murray KT (2011) Interactions between sea turtles and dredge gear in the U.S. sea scallop (*Placopecten magellanicus*) fishery, 2001–2008. *Fish Res* 107:137–146
- Musick J, Limpus C (1997) Habitat utilization and migration in juvenile sea turtles. In: Lutz PL, Musick JA (eds)

- The biology of sea turtles. CRC Press, Boca Raton, FL, p 137–163
- NMFS (National Marine Fisheries Service) (2008) Recovery plan for the Northwest Atlantic population of the loggerhead turtle (*Caretta caretta*), 2nd revision. NMFS USFWS, Silver Spring, MD
- Palka DL (2006) Summer abundance estimates of cetaceans in US North Atlantic navy operating areas. Northeast Fish Sci Cent Ref Doc 06-03, US Department of Commerce, Woods Hole, MA
- Polovina JJ, Balazs GH, Howell EA, Parker DM, Seki MP, Dutton PH (2004) Forage and migration habitat of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the Central North Pacific Ocean. Fish Oceanogr 13:36–51
- Polovina JJ, Uchida I, Balazs GH, Howell EA, Parker DM, Dutton PH (2006) The Kuroshio extension bifurcation region: a pelagic hotspot for juvenile loggerhead sea turtles. Deep-Sea Res II 53:326–339
- Seney EE, Musick JA (2007) Historical diet analysis of loggerhead sea turtles (*Caretta caretta*) in Virginia. Copeia 2007:478–489
- Smith WHF, Sandwell DT (1997) Global seafloor topography from satellite altimetry and ship depth soundings. Science 277:1957–1962
- Sonntag N, Schwemmer H, Fock HO, Bellebaum J, Garthe S (2012) Seabirds, set-nets, and conservation management: assessment of conflict potential and vulnerability of birds to bycatch in gillnets. ICES J Mar Sci 69:578–589
- TEWG (Turtle Expert Working Group) (2009) An assessment of the loggerhead turtle population in the western North Atlantic Ocean. NOAA Technical Memorandum NMFS-SEFSC-575, US Department of Commerce, Miami, FL
- Townsend DW, Thomas AC, Mayer LM, Thomas MA, Quinlan JA (2006) Oceanography of the Northwest Atlantic continental shelf, Chapter 5. In: Robinson AR, Brink KH (eds) The sea: the global coastal ocean: interdisciplinary regional studies and syntheses, Vol 14a. Harvard University Press, Boston, MA, p 119–168
- Wallace BP, Avens L, Braun-McNeill J, McClellan CM (2009) The diet composition of immature loggerheads: insights on trophic niche, growth rates, and fisheries interactions. J Exp Mar Biol Ecol 373:50–57
- Wallace BP, Lewison RL, McDonald SL, McDonald RK and others (2010) Global patterns of marine turtle bycatch. Conserv Lett 3:131–142
- Warden ML (2011) Modeling loggerhead sea turtle (*Caretta caretta*) interactions with US mid-Atlantic bottom trawl gear for fish and scallops, 2005–2008. Biol Conserv 144: 2202–2212
- Warden ML, Murray KT (2011) Reframing protected species interactions with commercial fishing gear: moving toward estimating the unobservable. Fish Res 110: 387–390
- Welsh AH, Cunningham RB, Donnelly CF, Lindenmayer DB (1996) Modelling the abundance of rare species: statistical models for counts with extra zeros. Ecol Modell 88: 297–308
- Wiens G (1989) Spatial scaling in ecology. Funct Ecol 3(4): 385–397
- Yoder JA, O'Reilly JE, Barnard AH, Moore TS, Ruhsam CM (2001) Variability in coastal zone color scanner (czcs) chlorophyll imagery of ocean margin waters off the US east coast. Cont Shelf Res 21:1191–1218
- Zydelis R, Lewison RL, Shaffer SA, Moore JE and others (2011) Dynamic habitat models: using telemetry data to project fisheries bycatch. Proc R Soc Lond B 278: 3191–3200

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