Temporal patterns of target catch and sea turtle bycatch in the US Atlantic pelagic longline fishing fleet

Connie Y. Kot, Andre M. Boustany, and Patrick N. Halpin

Abstract: Sea turtle bycatch in pelagic longline fishing gear is an ongoing threat to the conservation of sea turtle populations. However, these bycatch events do not occur uniformly in space or time. Leatherback (*Dermochelys coriacea*) and loggerhead (*Caretta caretta*) bycatch rates reported in large fishing regions exhibited different degrees of interannual variability. Target catch and sea turtle bycatch in most regions displayed strong periodicity that corresponded to seasons (~365 days) and/or moon phase (~29 days). When trends in catch and bycatch rates were examined by month and moon phase, the significant periods of higher and lower catch and bycatch related to swordfish (*Xiphias gladius*), yellowfin tuna (*Thunnus albacares*), and sea turtle temporal distributions in foraging and spawning/nesting, oceanographic and prey conditions, and foraging behavior. Catch and bycatch rates tended to depend more on a seasonal rather than a lunar time scale, although there is likely an interaction between the two. These findings provide insights to the susceptibility of target catch and bycatch, regional and temporal patterns of fishing effort, and potential guidance for resource management and conservation.

Résumé : La capture accessoire de tortues marines par les palangres pélagiques constitue toujours une menace pour la conservation des populations de tortues marines. Cependant, ces événements de captures accessoires ne se répartissent pas uniformément dans l'espace et le temps. Les taux de capture des tortues luths (*Dermochelys coriacea*) et des caouanes (*Caretta caretta*) signalés dans les grandes régions de pêche affichent des degrés divers de variabilité interannuelle. Dans la plupart des régions, les captures ciblées et les captures accessoires de tortues marines suivent une périodicité marquée qui correspond aux saisons (~365 jours) et/ou aux phases de la lune (~29 jours). L'examen des tendances dans les taux de captures ciblées et de captures accessoires en fonction des mois et des phases lunaires montre que les périodes significatives plus élevées et plus basses de captures ciblées et accessoires correspondent aux répartitions temporelles de la recherche de nourriture et de la fraie/nidification, ainsi qu'aux conditions océaniques, à l'état des proies et au comportement alimentaire, chez l'espadon (*Xiphias gladius*), l'albacore à nageoires jaunes (*Thunnus albacares*) et les tortues marines. Les taux de captures ciblées et accessoires tendent à dépendre plus d'une échelle temporelle saisonnière que lunaire, bien qu'il y ait vraisemblablement une interaction entre les deux. Ces résultats ouvrent des perspectives sur la vulnérabilité à la capture ciblée et accessoire et sur les patrons régionaux et temporels de répartition de l'effort de pêche et ils permettent de formuler des recommendations potentiellement utiles pour la gestion et la conservation.

[Traduit par la Rédaction]

Introduction

Nontarget sea turtle catch, or bycatch, can occur when turtles feed directly on bait or are entangled while migrating across regions where large amounts of fishing gear are present (Witzell 1999; Pinedo and Polacheck 2004). Sea turtle bycatch in longline fishing gear is an ongoing threat to sea turtle populations and conservation (James et al. 2005*c*; Lewison and Crowder 2007). Interactions between sea turtles and longlines have been known to cause serious injuries and mortality, prompting large-scale, mandatory mitigation measures including time–area closures and gear modifications. In the western north Atlantic, the US commercial pelagic longline fishery has approximately 80–100 active vessels (National Marine Fisheries Service 2006) that mainly target *Thunnus* spp. (yellowfin tuna (*Thunnus albacares*) and bigeye tuna (*Thunnus obesus*)) and swordfish (*Xiphias gladius*) (Sakagawa et al. 1987; Witzell 1999). An estimated 4000 sea turtles, mainly leatherbacks (*Dermochelys coriacea*) and loggerheads (*Caretta caretta*), were caught in this multispecies fishery in 1999 and 2000 (Yeung 2001).

Bycatch rates are influenced by temporal dynamics of the fishery as well as by the life history and biology of the tar-

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get and bycatch species. Although sea turtles are widely distributed throughout the Atlantic (Ferraroli et al. 2004; Hays et al. 2004), they often use regular migration corridors (Morreale et al. 1996) or oceanic areas (Eckert 2006) where they concentrate during specific seasons due to prey availability and nesting behavior (Shoop and Kenney 1992; Epperly et al. 1995). Likewise, target fish have seasonal movement patterns based on feeding and spawning behavior (Govoni et al. 2003; Arocha 2007), leading to uneven fishing effort, and consequently sea turtle bycatch rates, throughout the year. Fishers are usually aware of the resulting seasonality of their interactions with sea turtles, in some cases referring to these periods as “turtle season” (Bleakney 1965).

One mitigation tool to reduce bycatch is the use of time–area closures where the purpose is to limit fishing in regions where bycatch has been historically high (Witherell and Pautzke 1997; Auster and Shackell 2000). However, past bycatch rates are not necessarily indicators of future bycatch probability, especially when bycatch events are rare. Gaining a better understanding of the temporal variability and temporal patterns of bycatch rates is necessary to examine the potential utility for time–area closures in any specific region. Target catch and bycatch rates and variability in the US Atlantic longline fishery over various temporal scales and regions are examined here. Knowledge of bycatch temporal patterns can aid in the management of this fishery and contribute to the recovery of vulnerable sea turtle populations.

Materials and methods

Pelagic longline fishing effort data

The US National Oceanic and Atmospheric Administration (NOAA) Southeast Fisheries Science Center (SEFSC) requires data to be collected from Atlantic longline fisheries using a fisheries logbook system. Data from 1986 onward are publicly available online (Southeast Fisheries Science Center 2006). Sea turtle interactions were not recorded until 1992; therefore, earlier years were not included in this study. Since logbook data are self-reported, caveats include potential errors such as misreporting or underreporting of effort (gear characterizations), catch, and bycatch (Johnson et al. 1999). However, logbook data were used in this study, as opposed to observer collected data, due to the much larger sample size (>179 000 logbook sets versus <5000 observed sets). Although observer data showed significantly higher sea turtle bycatch when compared with logbook data, Johnson et al. (1999) found that temporal patterns were similar in the two data sets.

Regions were adapted from the NOAA SEFSC longline fishing regions (Cramer and Adams 1999; Beerkircher et al. 2002): Caribbean, Gulf of Mexico, Florida East Coast, South Atlantic Bight, Mid-Atlantic Bight, Northeast Coastal, Northeast Distant, Sargasso, North Central Atlantic, Tuna North, and Tuna South (Fig. 1). Longline fishing regions were analyzed separately, as large differences in seasonality and oceanography were expected to result in different temporal patterns among regions. Records/sets were excluded if they were outside the study region or suspect of error (i.e., the location reported was not on the border of or inside a designated longline fishing region in the Atlantic Ocean, any date information was missing, or the number of hooks set was <101).

Logbook data from 1992 to 2005 on the gear set date, location, number of sea turtles caught, number of finfish caught, and the number of hooks deployed were extracted from the datasheets. The total individuals of finfish catch (swordfish, bigeye tuna, bluefin tuna, yellowfin tuna, albacore tuna, blackfin tuna, other tuna, dolphin, wahoo, king mackerel, escolar, greater amberjack, bonito, and skipjack) and total individuals of sea turtle bycatch (leatherback, loggerhead, Kemp’s ridley, green, and other turtles) were summed for each set to calculate averages over all years. Since swordfish and yellowfin tuna composed the majority of the catch and loggerhead and leatherback sea turtles composed the majority of the bycatch, these four major species were examined individually as well. Variables included three target catch per unit effort rates and three sea turtle bycatch per unit effort rates (Table 1). The number of hooks was used as the effort unit because the number of hooks varied greatly by set (range 101–2600). Although catchability of each hook may vary depending on a number of factors, including the time deployed and location within the set (Ward 2008), it was assumed that hooks were independent, similar in catchability, and equally accessible to finfish and sea turtles to maintain simplicity. In addition, preliminary analyses showed hooks and sets were highly correlated and overall results did not change when analyzing catch and bycatch rates by hooks or by sets.

NOAA longline fishing regions (Fig. 1) were assigned to all sets that fell within or on the northern or western border of a longline fishing region. For each region, catch composition was examined to determine the percentage of catch consisting of yellowfin tuna, swordfish, or other target fish and bycatch composition was examined by the percentage of sea turtles consisting of leatherbacks, loggerheads, or other species. About 94% of pelagic longline sets from 1992 to 2005 were available (169 094 records) for analysis.

Data on the fraction of moon illuminated (range from 0 being new moon to 1 being full moon) for all days, 1992–2005, with Eastern Standard Time Zone and midnight reference times (US Naval Observatory 2008) were applied to every set based on the begin date of the fishing set. Values were grouped to reduce the effects of many zeros found in the raw data by including enough data within the bins while minimizing the loss in moon phase resolution. A total of 15 moon phases of 0.07 increments (i.e., 0–0.06, 0.07–0.13, etc.) with one group of 0.03 (0.98–1) was used that most closely correlated with a 29.5 day lunar periodicity. Therefore, moon phase 1 represents the moon at its darkest levels, while moon phase 15 represents the moon at its brightest. This also allowed for bins to coincide with days, which makes for a realistic time frame with regard to implementation of management measures when compared with the use of the fraction of the moon illuminated. Average catch and bycatch rates over all years were calculated for each moon phase as well as for each month.

Temporal patterns and temporal variability

Interannual variability of sea turtle bycatch

Analyses of bycatch rates were examined as an aggregate

Fig. 1. NOAA SEFSC Atlantic longline fishing regions and current NOAA marine managed areas pertaining to longline gear with annual time periods of fishing regulation or restriction and date that it went into effect in parenthesis. CAR, Caribbean; FEC, Florida East Coast; GOM, Gulf of Mexico; MAB, Mid-Atlantic Bight; NCA, North Central Atlantic; NEC, Northeast Coastal; NED, Northeast Distant; SAB, South Atlantic Bight; SAR, Sargasso; TUN, Tuna North; TUS, Tuna South.

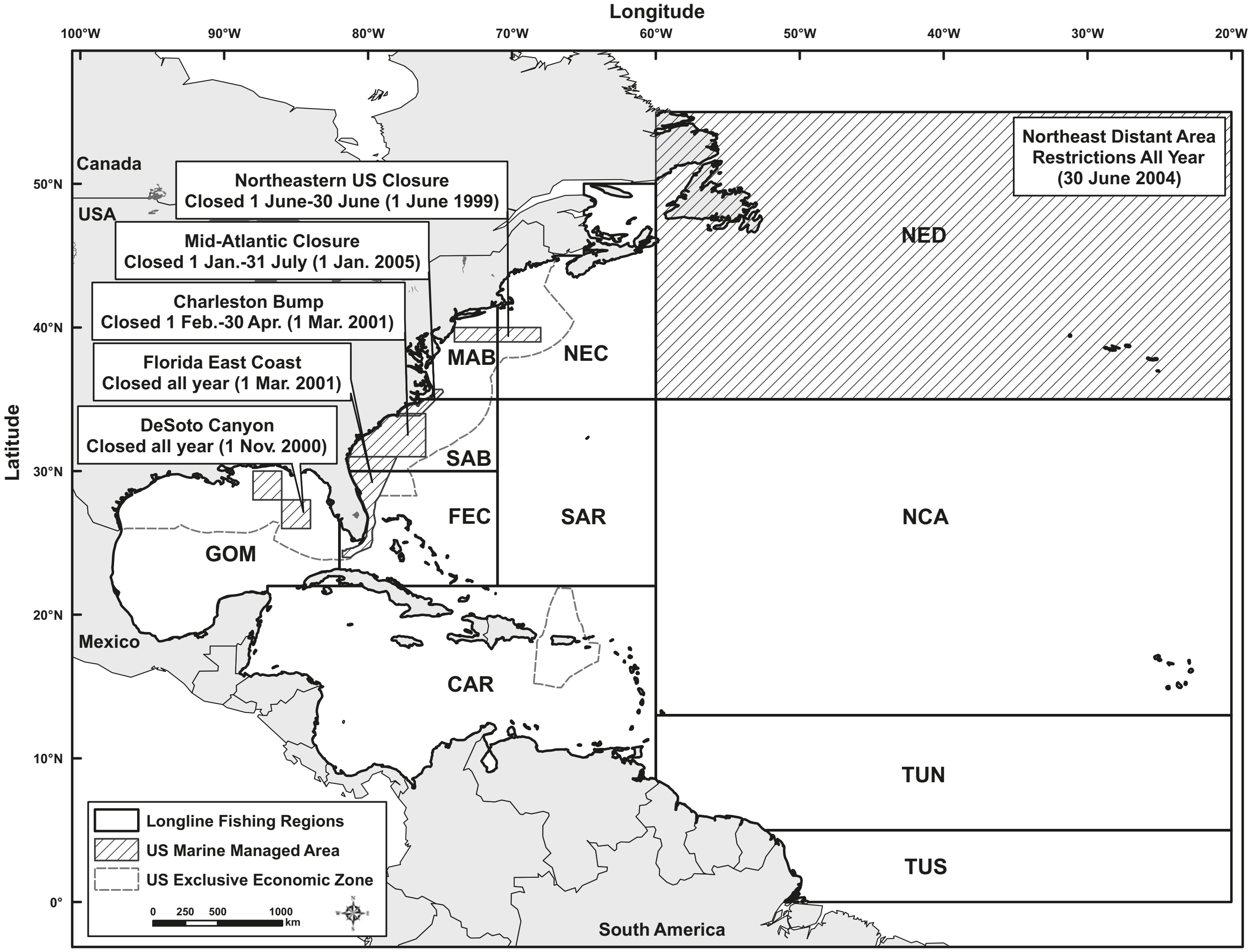


Table 1. Catch and bycatch rates examined for temporal patterns and temporal variability.

Catch and bycatch rate	Definition
Catch per unit effort	
CPUE	Total finfish catch/number of hooks set
SPUE	Swordfish catch/number of hooks set
YPUE	Yellowfin tuna catch/number of hooks set
Bycatch per unit effort	
BPUE	Total sea turtle bycatch/number of hooks set
LBPUE	Leatherback bycatch/number of hooks set
LHPUE	Loggerhead bycatch/number of hooks set

as well as individually for certain species. The analysis of an overall bycatch rate was included because currently all sea turtles are protected under the US Endangered Species Act and a high rate of sea turtle bycatch, regardless of species, is a cause for concern. However, sea turtle species have distinctly different distributions and behaviors in foraging, migratory movements, and bycatch. Therefore, the temporal pattern of bycatch was examined for the interannual variability of leatherback bycatch per hook and loggerhead bycatch per hook, as the majority of sea turtle bycatch in the US Atlantic pelagic longline fishery comprised these two species. For this analysis, the total number of leatherbacks and loggerheads within each region was summed for each month of the time series. These were divided by the total number of hooks in that region per month to calculate the total number of leatherbacks per hook and loggerheads per hook for each region per month. Values were then averaged across years (n = 14) to determine the mean bycatch per month per region and a coefficient of variation (CV = standard deviation/mean) was calculated for each of these region/months for both leatherback and loggerhead catch per hook. To control for the possible interannual variability due to time–area closures, which were in effect during certain years and not others during 1992–2005 (Fig. 1), any set that would have been in a subsequent closed area was removed from this analysis. CVs were not calculated for months with less than seven different years of data (half of the time series) due to concerns over small sample sizes.

Periodicity of catch and bycatch

Periodicity of target catch and bycatch rates reported in fishing regions within the Atlantic was investigated using the Fast Fourier Transform (FFT) (Cooley and Tukey 1965) for spectral analysis. The FFT, a nonparametric linear process for determining the frequency of events in time (Smith 1998), was applied to the number of hooks set and the six catch and bycatch rates (Table 1) using MatLab Signal Processing Toolbox 6.9 (Mathworks 2008). As the presence of fishing sets occurred at temporal scales (days) much shorter than those of interest (monthly, seasonally), the Nyquist sampling theorem, (Shannon 1949) which requires sampling to occur at the rate that is equal to or greater than twice the frequency of the event to ensure a signal's detection, was assumed to be satisfied. To examine the effect of long-term (greater than several years) trends, data were also analyzed using a Hilbert Huang Transform (HHT) (Huang et al. 1998). The HHT processes nonstationary signals, unlike the FFT, which assumes stationarity. Results of the FFT and HHT analyses were similar in that strong peaks did not change periods, and therefore, only results from the FFT are presented.

Identifying significant time periods

When strong peaks indicated periodicity, post hoc analyses were applied in each region according to the specific time periods identified in the spectral analysis. Multiple Wilcoxon's signed-rank tests (nonparametric comparisons; Wilcoxon 1945) were used to compare monthly average rates with a false discovery rate adjustment (Benjamini and Yekutieli 2001) to reduce the possibility of Type I error from multiple comparisons. The significance level (α = 0.05) was adjusted for the number of comparisons: $p < 0.01611$ for 12 months. The Wilcoxon test is recommended to be the most robust method available (Delucchi and Bostrom 2004), even with the caveat that many zeros, as a result of sea turtle bycatch being a rare event, may reduce the power of the Wilcoxon test by increasing the possibility of Type II error. Given the distribution of the data and as lunar comparisons showed a unidirectional trend, nonparametric linear regressions with Kendall's rank correlation coefficients (τ) were used to identify slopes significantly different from zero and to determine the catch and bycatch trends with moon phases (StatsDirect 2008). These analyses gave further insight in determining which particular time period exhibited significantly higher or lower target catch and sea turtle bycatch.

Comparing annual and lunar time scales

In addition, regression tree analysis was used to examine the relative importance of specific time periods identified in the spectral analysis (Breiman et al. 1984). Classification and regression trees (CARTs) are used to create a decision tree for predicting the response variable from one or more predictor variables; classification trees are used for discrete variables, while regression trees are used for continuous variables. The methodology outlined in Breiman et al. (1984) was used for both creation of the total regression tree and subsequent pruning of the tree to highlight significant branching nodes. For tree pruning, a 10-fold cross-validation was used to compute the additional cost of each node by partitioning the total tree into 10 subsamples. For each subsample, a tree was fit to the remaining data and it was used to predict the subsample. All subtrees were then combined to calculate the cost for each node in the total tree. Next, the number of nodes versus the cumulative cost was examined where the cost of a node was the mean squared error over the misclassification cost of the observations in any given node. The minimal cost tree is usually the one that contains all of the nodes, as each one is marginally informative in predicting the total likelihood of the response variable of interest. To highlight more important branch nodes, the cost versus node structure was used to compute the smallest tree within 1 standard error of the minimum cost tree.

Results

Pelagic longline fishing effort

In general, there were more fishing sets in US coastal, southern regions (i.e., Gulf of Mexico, Florida East Coast) than regions in the north or offshore (i.e., North Central Atlantic, Northeast Distant regions) (Table 2). Swordfish tended to be caught more frequently than other target species, but it was also apparent that other species were important contributors to catch. Leatherback sea turtles had the highest percentage of bycatch for most regions when compared with loggerheads or other sea turtles combined, although more loggerheads were caught when summed across regions due to the high number caught within the Northeast Distant region. When comparing sets across regions that were dominated by yellowfin tuna (>50% of fish caught were yellowfin tuna) with those dominated by swordfish (>50% of fish caught were swordfish), sets with swordfish were significantly deeper and had higher numbers of lightsticks per set and lower numbers of hooks set but higher sea turtle bycatch per hook (Wilcoxon's signed-rank test, $p < 0.0001$).

Temporal patterns and temporal variability

Interannual variability of sea turtle bycatch

In each region, bycatch rates of loggerhead and leatherback sea turtles were compared by month, showing high rates for both species in the Northeast Distant during the summer and fall (Figs. 2*a* and 2*b*). High rates of leatherback

Table 2. Total number of sets, fish catch, and sea turtle bycatch and percent composition reported in NOAA SEFSC Atlantic longline fishing regions during 1992–2005 (the bolded number is the highest percentage per category).

		Fish catch (%)				Sea turtle bycatch (%)			
Region	Total sets (*n*)	Yellowfin tuna	Swordfish	Other	Total catch (*n*)	Leatherback	Loggerhead	Other	Total bycatch (*n*)
Caribbean	9 611	7.8	**69.4**	22.8	148 880	**44.1**	40.6	15.3	202
Gulf of Mexico	61 299	**52.0**	20.0	28.0	1 013 657	**85.2**	8.1	6.8	621
Florida East Coast	22 557	10.4	**55.5**	34.1	283 012	**50.4**	43.9	5.7	123
South Atlantic Bight	19 067	11.8	39.3	**48.9**	483 577	**57.1**	35.4	7.5	147
Mid-Atlantic Bight	24 276	40.0	19.7	**40.3**	500 964	**64.0**	30.5	5.5	505
Northeast Coastal	13 845	30.0	25.5	**44.5**	280 028	40.9	**51.6**	7.6	673
Northeast Distant	9 590	1.9	**81.7**	16.5	253 858	30.7	**63.6**	5.7	4203
Sargasso	1 562	6.7	**49.3**	44.0	25 772	35.5	**58.1**	6.5	62
North Central Atlantic	4 116	5.1	**68.1**	26.8	74 214	**43.8**	38.2	18.0	178
Tuna North	1 940	**40.4**	31.1	28.5	41 362	**80.9**	11.7	7.4	94
Tuna South	1 231	16.4	**60.3**	23.3	41 035	**59.3**	7.4	33.3	27

bycatch were seen in the tropical offshore waters (Sargasso, North Central Atlantic, Tuna North, and Tuna South) (Fig. 2*a*), while loggerheads had high rates in the Northeast Coastal region in the winter months (Fig. 2*b*). Interannual comparisons of leatherback and loggerhead bycatch showed variation among years, with the range of CVs differing by species (Figs. 2*c* and 2*d*). Loggerhead bycatch was generally more variable interannually (maximum CV = 17) than leatherback bycatch (maximum CV = 4.43). Loggerhead and leatherback bycatches were highly variable in May and November in the Northeast Distant region, which are the months that correspond to the beginning and end of the fishing season in this area. However, both sea turtle species had less variable bycatch rates in July through October in the Northeast Distant (CV < 1.5) (Figs. 2*c* and 2*d*), a time when bycatch rates for both species are high (Figs. 2*a* and 2*b*). Leatherback bycatch rates showed greater interannual stability in the Caribbean and Gulf of Mexico where CVs among years were generally less than 1.5 for all months (Fig. 2*c*). In contrast, the coastal and more northern regions (Florida East Coast, South Atlantic Bight, Mid-Atlantic Bight, and Northeast Coastal) had greater variation in leatherback bycatch among years (CV > 2 for most months) (Fig. 2*c*).

Periodicity of catch and bycatch

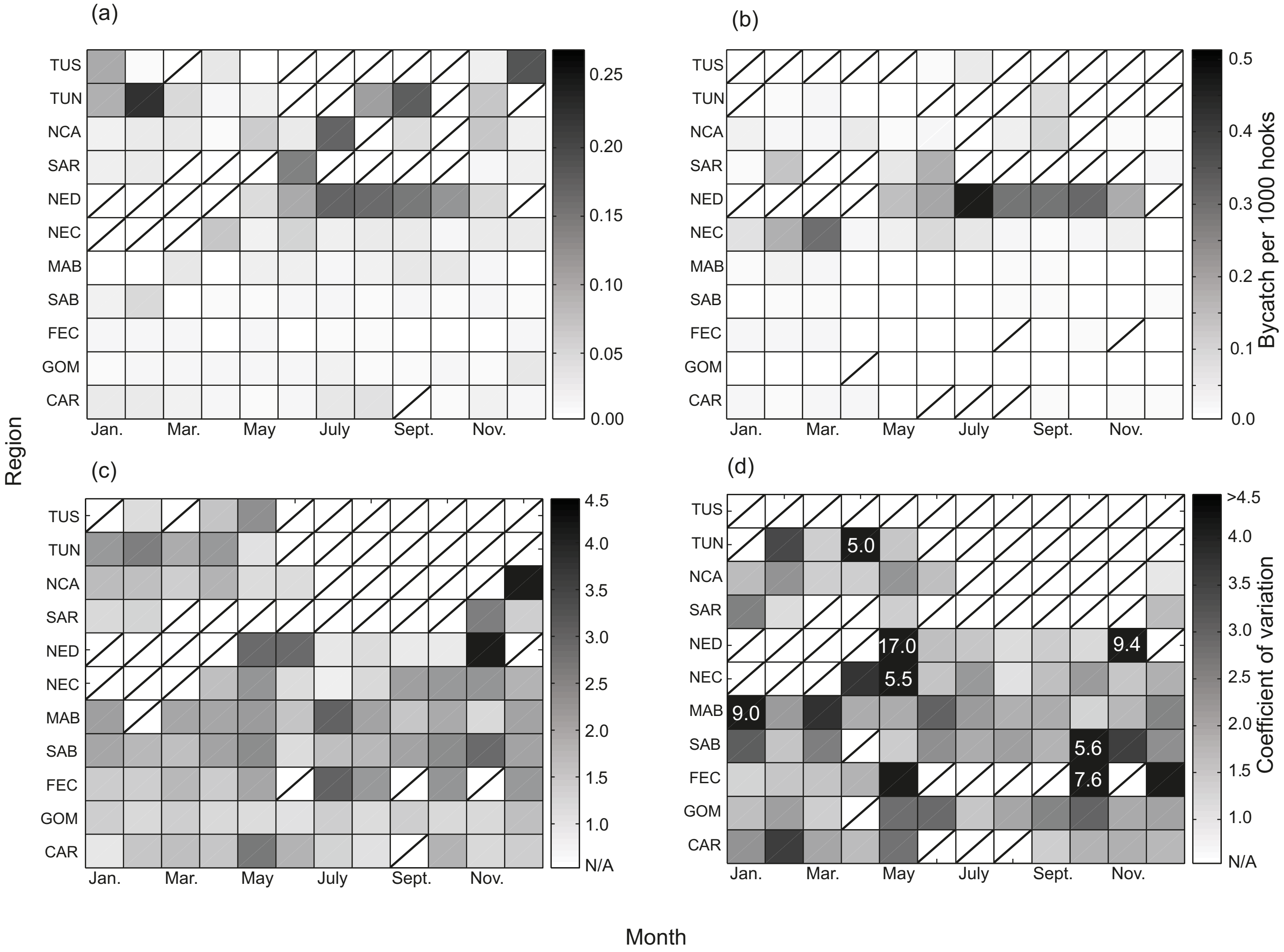
Results from the spectral analysis showed that most regions exhibited a strong annual/seasonal periodicity (~365 days) for target catch and sea turtle bycatch rates (Figs. 3*a* and 3*b*). Annual peaks in the measures of bycatch were less distinct and of a lower power than for catch, likely due to much reduced sample sizes for these variables. The second major periodicity that emerged from the spectral analysis for both measures of catch and bycatch was a lunar period (~29 days) (Figs. 3*b* and 3*c*). Lunar periodicity was usually found in addition to a stronger annual periodicity, although of lower power, and was most prominent in the more southern regions. For some species in certain regions (i.e., leatherbacks in the Gulf of Mexico), lunar periodicities were present without an annual peak (Fig. 3*c*, right panel). Peaks were less distinct, or even absent, for both catch and bycatch variables for regions where fishing effort and/or catch rates were low, likely due to decreased sample size. However, even in some regions with high catch rates (i.e., yellowfin tuna in the Florida East Coast), there was no evidence of either a monthly or an annual periodicity (Fig. 3*d*).

Identifying significant time periods

Since many regions showed a strong annual period in the spectral analysis, rates were examined over the course of the year using multiple Wilcoxon's signed-rank tests for each month or nonparametric regression for moon phase to determine specific periods of high or low target catch and sea turtle bycatch. This question was important to help determine the feasibility of specific periods of time that can be realistically managed by a static time–area restriction to reduce bycatch. For example, should the results show evidence of higher than average bycatch in June, measures for reducing bycatch would benefit most if they were in place during June.

Significant differences emerged, but there was not a clear, general pattern across regions. When target catch variables

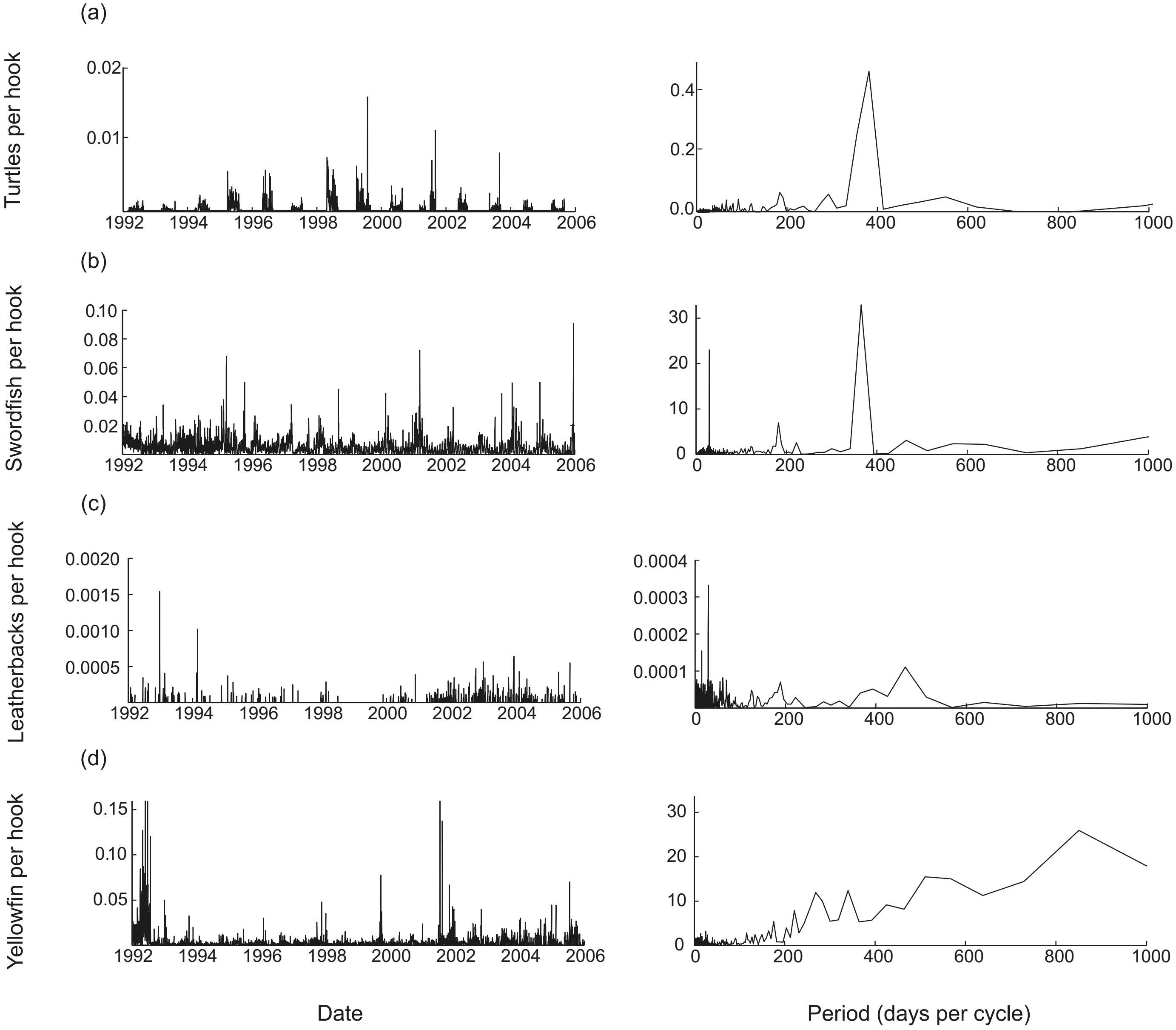
Fig. 2. Matrix of regional and monthly bycatch rates (catch per 1000 hooks) for (*a*) leatherbacks and (*b*) loggerheads and matrix of CVs (= standard deviation/mean) for (*c*) leatherbacks and (*d*) loggerheads excluding sets that fell within a closed area. For CVs, the maximum value was 4.5 except where noted by a number (the exact CV value) and months/regions in open cells were not analyzed because of limited data. Hatched cells represent zero bycatch for Figs. 2*a* and 2*b* and "not analyzed" for Figs. 2*c* and 2*d*. See Fig. 1 for definition of regions.



were plotted annually, regions fell into one of three general patterns (Fig. 4): (*i*) swordfish and yellowfin tuna catches were out-of-phase, mostly seen in regions with a greater abundance in yellowfin tuna/mixed catch in set compositions such as the Gulf of Mexico, Mid-Atlantic Bight, Northeast Coastal, Sargasso, and Tuna North regions, (*ii*) swordfish catch decreased in spring and increased in fall, while yellowfin tuna catch showed little annual change, mostly seen in regions with more swordfish such as the Caribbean, Florida East Coast, South Atlantic Bight, and Northeast Distant regions, or (*iii*) swordfish catch increased in the spring and decreased in the fall, while yellowfin tuna catch showed relatively little annual change, mostly seen in regions with more swordfish catch and farther offshore such as the North Central Atlantic and Tuna South regions.

Multiple comparisons using the Wilcoxon test for specific months (i.e., January versus all other months, February versus all other months, etc.) showed higher sea turtle bycatch rates in the winter for tropical and more southern regions, while temperate regions exhibited higher bycatch rates in summer and fall. For example, the Florida East Coast showed high bycatch in the winter, with significantly higher BPUE and LHPUE (see Table 1 for definitions) in January–March ($p < 0.0065$) (Fig. 4*c*). Other subtropical and tropical regions that showed significantly higher sea turtle bycatch rate variables (Table 1) in the winter include the Gulf of Mexico (December, $p < 0.0001$), Sargasso (February, $p < 0.0001$), Tuna North (February, $p < 0.0001$), and Tuna South (December–January, $p < 0.00021$) regions (Figs. 2*a* and 2*b*). One exception was the temperate Northeast Coastal region where bycatch also peaked in the winter to spring (February–March, $p < 0.0001$) (Figs. 2*a* and 2*b*). Temperate regions that showed an increase in bycatch rates in the summer months included the Northeast Coastal (June–July, $p < 0.008$) and Northeast Distant (July, $p < 0.0039$) regions (Figs. 2*a* and 2*b*). For the Mid-Atlantic Bight, bycatch variables were significantly higher around September–October ($p < 0.0014$) and significantly lower in the winter (December–February, $p < 0.0088$), corresponding closely to YPUE (Fig. 4*e*). Other regions that showed significantly

Fig. 3. Representative spectral analysis graphs of catch and bycatch rates over time (left) and power of periodic peaks (right) for (*a*) sea turtle per hook in the Northeast Distant showing strong yearly period, peaking at 377.4 days, (*b*) swordfish per hook in the Gulf of Mexico showing a lunar and a yearly periodicity, peaking at 29.2 and 364.6 days, respectively, (*c*) leatherback per hook in the Gulf of Mexico showing a lunar periodicity without a yearly period, peaking at 29.6 days, and (*d*) yellowfin tuna per hook in the Florida East Coast showing no strong period, with no prominent peak.

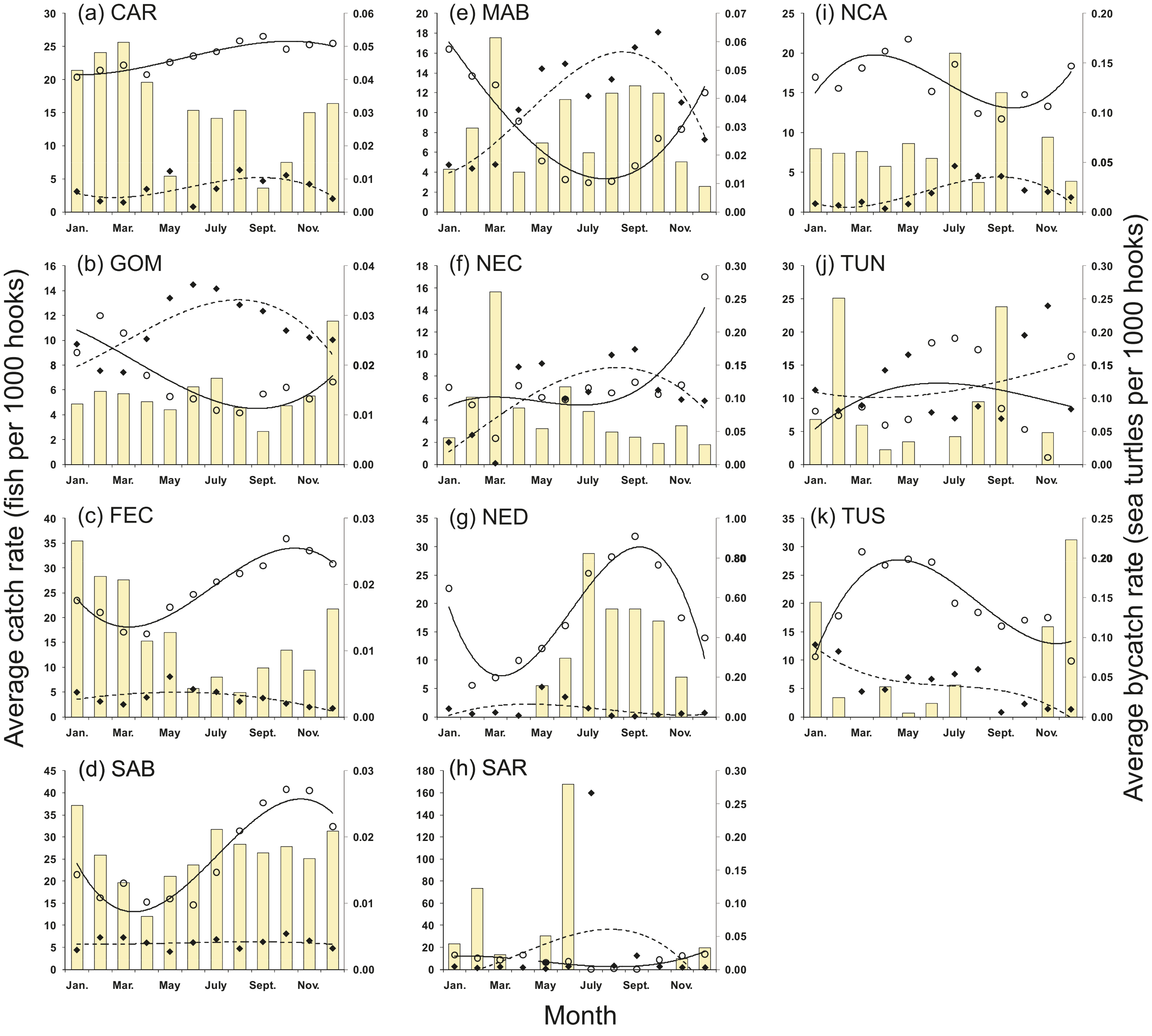


higher bycatch in the fall included the Northeast Coastal (September–October, $p < 0.00021$) and North Central Atlantic (September, $p < 0.0036$) regions.

As catch and bycatch variables tended to vary linearly with percent moon illumination, catch and bycatch were examined with moon phase through the use of nonparametric linear regressions. All regions displayed at least one significant nonzero slope for the number of hooks, catch, or bycatch variables (Table 3; Fig. 5). In general, the significant trend for target CPUE, SPUE, and YPUE was an increase with fullness of the moon, especially obvious in regions with more swordfish or mixed catch, such as the Caribbean, Mid-Atlantic Bight, Northeast Coastal, Northeast Distant, Sargasso, North Central Atlantic, and Tuna South regions. The exception was the South Atlantic Bight where there was a slight although significant decrease in CPUE and SPUE with a brighter moon (Table 3; Fig. 5*d*). In addition, YPUE decreased while SPUE and BPUE increased with increasing moon illumination in yellowfin tuna catch dominated regions, such as the Tuna North and Gulf of Mexico regions (Figs. 5*b* and 5*j*).

Similar to target catch, an increase in sea turtle bycatch with lunar illumination was more significant in tropical, more southern regions such as the Caribbean, Gulf of Mexico, Florida East Coast, and South Atlantic Bight (Table 3; Fig. 5). It was especially apparent in the Gulf of Mexico, where all bycatch per hook variables were significantly lower with the new moon and significantly higher with the

Fig. 4. Average catch rates (swordfish per 1000 hooks and yellowfin tuna per 1000 hooks) and bycatch rates (sea turtles per 1000 hooks) per set reported in 1992–2005 for months in the 11 longline fishing regions. Circles represent swordfish per hook, diamonds represent yellowfin tuna per hook, solid lines represent swordfish per hook cubic spline, broken lines represent yellowfin tuna per hook cubic spline, and bars represent total sea turtles per hook. See Fig. 1 for definition of regions.



full moon (Fig. 5*b*; Table 3). On the other hand, there was a slightly significant negative slope with lunar illumination and bycatch in the temperate Northeast Distant region (Fig. 5*g*; Table 3), with significantly higher BPUE and LHPUE towards the newer moon and significantly lower LHPUE near the full moon (Table 3).

Comparing annual and lunar time scales

As both season and moon phase appeared to have significant effects on catch and bycatch rates, regression tree analyses for each region were performed to examine the hierarchical nature of the two temporal predictor variables: raw percent moon illumination (0–100) and day of the year (1–365). A separate regression tree was created with each catch or bycatch rate as the response variable (Table 1). Results from the regression tree analysis were generally congruent with the results from the spectral analysis, multiple signed rank tests, and regression analyses. For bycatch and catch variables that showed indication of day and moon phase playing important roles in the previously mentioned methods, the regression tree analysis generally created pruned trees that showed branching nodes including both of these temporal variables. For example, swordfish catch per hook in the Gulf of Mexico saw an influence from both moon phase and season in the spectral analysis (Fig. 3*b*), the multiple monthly comparisons (Fig. 4*b*), and in the linear regression of moon phase (Table 2). Plotting the results from the Gulf of Mexico regression tree analysis also

Table 3. Lunar trend (median slope of nonparametric linear regression) for each region (Kendall's correlation coefficient τ: $p \leq 0.10$, *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$) (slopes not significantly different from zero ($p > 0.10$) are not shown).

	Lunar trend (median linear slope × 10^{-4})						
Region	Hook	CPUE	SPUE	YPUE	BPUE	LBPUE	LHPUE
Caribbean	–36 175***	7.78***	3.84***	1.69***	26.01***	0.02**	
Gulf of Mexico	–16 541**		4.5***	–2.84***	12.55***	0.01***	0.0103*
Florida East Coast	24 925***	2.99*		0.95*			0.00493*
South Atlantic Bight	58 020***	–7.53***	–1.16*	1.85***			0.00329**
Mid-Atlantic Bight	18 349***	7.6***	1.05***	1.64*			
Northeast Coastal	13 812*	6.28***	0.53*				
Northeast Distant		5.88***	2.96***		–3.81		–0.07*
Sargasso	–46 897*	8.57***	0.9*			0.01	
North Central Atlantic		5.45***	1.15*	0.65**			0.02*
Tuna North	27 720**	6.64**	3.88***	–2.32**		0.02*	
Tuna South		9.98***	3.55*	1.17*	7.04		

Note: See Table 1 for catch and bycatch rate definitions.

showed significant branch nodes for day of the year and moon phase, with the lunar trend falling out nested within the seasonal trend (Fig. 6*a*). Most often, day was the original or parent node that corresponded to the dominant peaks seen in the spectral analysis.

For variables that showed seasonal trends but no lunar trend, subsequent regression tree analysis showed only day of the year being a significant variable in the branching pattern of the final tree. Swordfish per hook in the Florida East Coast showed no lunar trend in either the spectral analysis (not shown) or the nonparametric regression analysis (Table 3) but did show a strong seasonal period in both the spectral analysis and multiple monthly comparisons (Fig. 4*c*). Likewise, the most parsimonious regression tree only contained branch nodes for day of the year (Fig. 6*b*).

Catch and bycatch variables that showed no strong peaks using the spectral analysis, or significant trends in either the multiple comparisons for month or nonparametric linear regression for moon phase, did not show significant branching patterns at any level using the regression tree methodology. Yellowfin tuna catch in the Florida East Coast showed no prominent peak in the spectral analysis (Fig. 3*d*), little annual seasonal change (Fig. 4*c*), and an insignificant slope with lunar illumination (Table 3; Fig. 5*c*). Likewise, calculating the Florida East Coast regression tree for yellowfin tuna within 1 standard error of the minimal cost tree collapsed all branches, yielding no useable nodes. If the tree was forced to include any nodes at all, a complex tree resulted that yielded little information on the relative importance of moon phase and day of the year to catch rates of yellowfin tuna in this region (Fig. 6*c*).

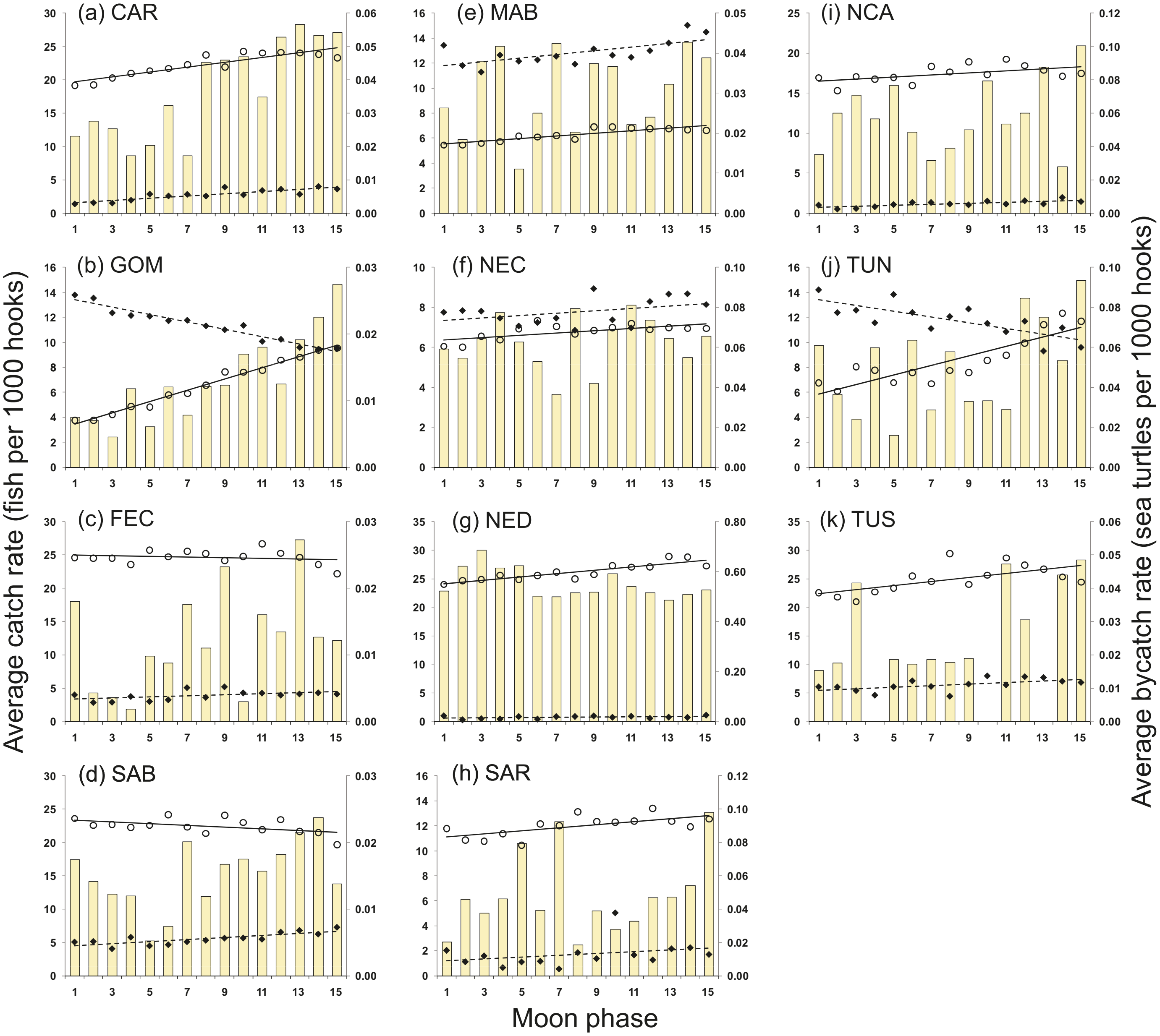
Discussion

Temporal patterns in target catch and sea turtle bycatch in the US Atlantic pelagic longline fishing fleet were found to vary regionally, interannually, monthly, and with moon phase. Results have shown that within specific regions, certain months had more interannual variation in bycatch than other months, with leatherback bycatch rates being generally more stable when compared with rates for loggerhead sea turtles. Along with these variations in bycatch rates, periods of a repeating pattern in catch and bycatch appeared at both annual and lunar time scales. Across regions, annual trends for catch averaged by month resulted in three distinct patterns related to seasonal distribution of fishing effort, catch, and bycatch. Lunar trends for catch and bycatch were mostly similar in having increased rates with increased moonlight, which may be related to catchability. Describing the temporal patterns of bycatch with each of these parts may facilitate in determining whether periods of high bycatch rates are anomalous or signals of a repeating pattern. Additionally, temporal patterns described here can help in the decision for possible fishing regulations mitigating sea turtle bycatch with the consideration of effects on target catch over time.

Interannual variability of sea turtle bycatch

The interannual variability of bycatch differed regionally and by species, which may be a function of differences in sea turtle distribution, foraging, migratory movements, and habitat. Leatherbacks are known to feed on planktonic gelatinous prey in the Northwest Atlantic where evidence of high prey abundance was seen in the summer and fall (James and Herman 2001; James et al. 2005*b*). This period of high foraging activity was also a time of high bycatch with little interannual variability, as seen in the Northeast Distant from July to October. In contrast, the months before and after this period (May–June and November) had reduced, but still high, bycatch rates with much greater interannual variability. Highly variable catch rates probably were a response to the underlying conditions present in the Northeast Distant during these time periods. Since leatherback and target fish species are linked to oceanographic conditions such as sea surface temperature (SST) (Watson et al. 2005; Gardner et al. 2008), time periods with more variable SST and the related densities of prey aggregation and productivity could result in more variable bycatch and catch rates. McMahon and Hays (2006) found that the northerly range extent of leatherback sea turtles appeared to be controlled by the 15 °C isotherm, which had a variable position within the Northeast Distant area during 1983–2002. Therefore, variability in SST may be expected to lead to interannual changes in leatherback presence and bycatch rates at the margins of the species' range. In addition, summer and early fall months are likely to have high average temperatures across

Fig. 5. Average catch rates (swordfish per 1000 hooks and yellowfin tuna per 1000 hooks) and bycatch rates (sea turtles per 1000 hooks) per set reported in 1992–2005 for moon phases (1, darkest, new moon; 15, brightest, full moon) in the 11 longline fishing regions. Circles represent swordfish per hook, diamonds represent yellowfin tuna per hook, solid lines represent swordfish per hook linear fit, broken lines represent yellowfin tuna per hook linear fit, and bars represent total sea turtles per hook. See Fig. 1 for definition of regions.



all years, but slight differences in timing among years for spring warming and fall cooling can lead to more variable bycatch rates in the spring and late fall.

In contrast with the high bycatch rates in the Northeast Distant, the east coast of the United States (Florida East Coast, South Atlantic Bight, Mid-Atlantic Bight, and Northeast Coastal regions) had much reduced bycatch rates for both loggerheads and leatherbacks. These regions also exhibited greater interannual bycatch variability, suggesting that periods of high sea turtle bycatch in these regions were not stable. In the Gulf of Mexico and Caribbean regions, relatively low sea turtle bycatch rates with low interannual variability were found, especially for the leatherback sea turtle (the regions' main sea turtle species caught), which would seem to make these regions and periods lower priority for sea turtle bycatch mitigation compared with other regions. However, the Gulf of Mexico and Caribbean regions' relatively high longline fishing effort (number of sets) and high number of sea turtles caught should be taken into account when assessing the US Atlantic longline fishery as a whole. Differences between these regions (Gulf of Mexico and Caribbean) and those north and along the east coast (Florida East Coast, South Atlantic Bight, Mid-Atlantic Bight, and Northeast Coastal) may be explained by the difference in the stability of the underlying oceanographic conditions that establish productivity, prey, and predator distributions. More tropical, southern regions generally have more stable temperatures among years (Dzhiganshin and Polonsky 1995),

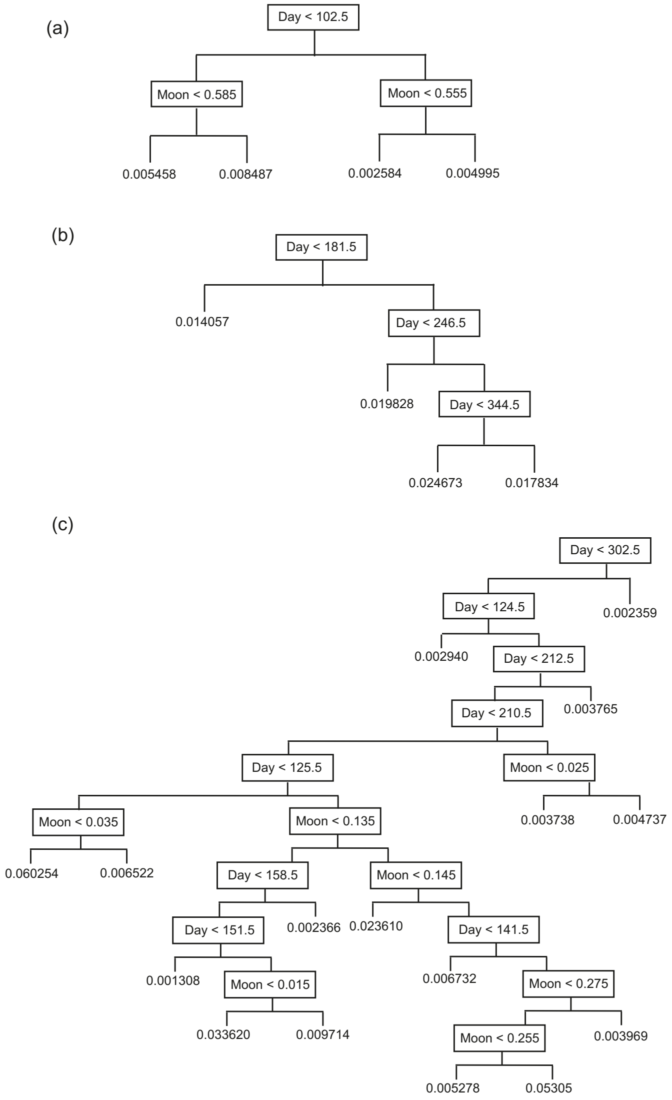


Fig. 6. Regression trees for (*a*) Gulf of Mexico swordfish catch per hook, (*b*) Florida East Coast swordfish catch per hook, and (*c*) Florida East Coast yellowfin tuna catch per hook (yes, branch towards left; no, branch towards right).

which will act to moderate interannual variability of productivity and prey and consequently stabilize bycatch rates. In contrast, temperate regions along the east coast of the United States will likely have greater oceanographic interannual variability (Dzhiganshin and Polonsky 1995), leading to variable prey and sea turtle distributions, followed by bycatch rates.

Annual leatherback sea turtle migrations from northern foraging areas southward are highly variable and can begin in late summer to winter (James et al. 2005*a*; Sherrill-Mix et al. 2008), usually triggered by declines in zooplankton prey abundance, which can be influenced by oceanographic conditions such as SST and chlorophyll *a* concentrations (Sherrill-Mix et al. 2008). High variability in the schedule of migration to foraging areas, and therefore abundance of sea turtles in certain areas within the Atlantic, can contribute to temporal bycatch variability. In contrast, the interannual timing and location of sea turtle nesting activity are generally known to be much more stable than foraging activity, which would lead to less variability in bycatch rates near sea turtle nesting sites in the coastal tropical and subtropical regions. Other subtropical and tropical regions (Sargasso, North Central Atlantic, Tuna North, and Tuna South) exhibited interannual variation that was relatively high for months where it was possible to calculate CVs. However, because there were a small number of fishing sets conducted in these regions, variability may be inflated due to low sample sizes, and therefore, it was difficult to draw firm conclusions on the stability of bycatch rates in these regions.

Leatherback sea turtle bycatch was generally seen to be less variable when compared with loggerhead sea turtles, which may be a reflection of foraging strategies. Not only are loggerhead sea turtles opportunistic feeders, they also have the flexibility to shift the main prey in their diets due to prey abundance (Seney and Musick 2007) or changes in their habitat use with development (i.e., neritic finfish versus benthic crustacean prey). Meanwhile, leatherbacks are known to specialize in pelagic gelatinous organisms (Lutcavage and Lutz 1986) and this foraging strategy may increase the stability of bycatch rates.

Periodicity of catch and bycatch

In most regions, the primary periodicity for yellowfin tuna catch, swordfish catch, and sea turtle bycatch rates appeared to be on a seasonal scale, with the secondary yet significant lunar periodicity more apparent in the southern regions. The four species studied in detail here are cosmopolitan and highly migratory, occupying different spatial and temporal niches so that seasonal and regional utilization was expected to depend on each species' individual needs. Mills (2008) found that time and intensity of moonlight in tropical zones were more steady annually than at higher latitudes because at higher latitudes, the number of dark hours changes greatly with season, with decreased influence of moonlight near the summer solstice. If behavioral patterns of target catch and bycatch are governed by moonlight, they will be more stable throughout the year at lower latitudes, which may explain why lunar periodicity in catch and bycatch was more prominent in southern regions compared with the northern regions.

Significant time periods for catch and bycatch

Monthly temporal patterns in subtropical and tropical regions with a majority of catch being yellowfin tuna and mixed species (i.e., Gulf of Mexico and Sargasso) showed a peak (based on results from the multiple comparisons) in yellowfin tuna catch in late spring – summer and a peak in swordfish catch in the winter, corresponding closely to spawning periods. In the Gulf of Mexico, yellowfin tuna spawn in May–August (Arocha et al. 2000, 2001) and swordfish spawn during December–May (dos Santos and Garcia 2005; Arocha 2007), correlating with high catch rates on longlines found during these periods. In other subtropical regions where swordfish was a large portion of the catch, high swordfish catch peaked in the spring (North Central Atlantic and Tuna South) or fall (Caribbean, Florida East Coast, and South Atlantic Bight regions) based on the multiple comparisons analyses. This annual trend corresponds to year-round swordfish spawning (Govoni et al. 2003), with peak spawning activity in April–June and October–December (Arocha and Lee 1996; Arocha 2007) in subtropical regions. However, these peaks were not apparent in the tropical Tuna North region, possibly because of relatively low fishing effort.

High rates of yellowfin tuna and swordfish catch occurred in their temperate feeding grounds in addition to their spawning grounds, which may be a result of fishers following the seasonal migrations of their targets (e.g., Pelletier and Magal 1996). Swordfish use temperate regions as feeding grounds when not breeding in warmer subtropical waters (Hoey and Mejuto 1991; Alvarado Bremer et al. 2005) and swordfish catch rates were found in this study to peak in the fall (Northeast Distant region) and winter (Mid-Atlantic Bight and Northeast Coastal regions), as shown by the multiple comparisons. In addition, temperate regions that exhibit a mix of target catch species had high yellowfin tuna catch in the summer–fall, also corresponding to adults dispersing to feed in areas outside the spawning grounds (Maury et al. 2001).

Juvenile and adult leatherback and loggerhead sea turtles also have annual patterns of migration for nesting and foraging in the Atlantic. High numbers of leatherback sea turtles caught in temperate regions during the summer–fall correspond to the migration of nesting and nonnesting turtles from the tropical and subtropical Atlantic after the winter nesting season across the open ocean and towards feeding areas in the northwest Atlantic (James et al. 2005*a*; Eckert 2006). Along with seasonal distributions of nesting and foraging leatherback sea turtles, the seasonal pattern of prey availability as a result of diel vertical migration behavior can contribute to variations in bycatch rates. For example, oceanic zooplankton are known to exhibit seasonal changes in their diel vertical migration behavior (e.g., Hays 1995), causing their availability to diving predators to change over time, which may in turn drive variations in predator diving (James et al. 2006). This seasonal change in diel vertical migration and the associated changes in turtle diving may be another cause of seasonal changes in bycatch rates. In contrast, large juvenile loggerheads usually are benthic feeders in coastal areas but are a large component of sea turtle longline bycatch in offshore regions. McClellan and Read (2007) have seen satellite-tagged loggerheads continue to use oceanic areas after spending time in neritic waters and before reproducing and it has been suggested that post-hatchlings move and develop within the North Atlantic gyre (Carr 1986), which may explain the presence of loggerhead bycatch in the Northeast Distant, Northeast Coastal, and Sargasso regions. Loggerheads migrate northwards after the May–September nesting season, mostly from the South Atlantic Bight and Florida East Coast, along the coast (Plotkin and Spotila 2002; McClellan and Read 2007) or continue to reside in subtropical/tropical latitudes (Henwood 1987; Morreale and Standora 2005). Throughout the year, loggerhead sea turtles are distributed from tropical to northern Atlantic waters, although they are found to migrate to the warmer subtropical and tropical waters in the winter (Morreale and Standora 2005). This increased presence of loggerheads in the winter coincided with the higher sea turtle bycatch rates seen in December–February for southern US longline fishery regions (i.e., Gulf of Mexico, Sargasso, Tuna North, and Tuna South regions).

Over all regions, the most common trend with moon phase was an increase in catch and bycatch with fullness of the moon, most apparent in tropical regions where swordfish or a mix of species dominated the catch composition of sets. The case of tropical regions having a tighter relationship with moon phase than temperate regions was supported by the spectral analysis, with the most prominent 29-day peaks appearing in these southern regions. Even though the effects of cloud cover on the moonlight and the realized light level due to season were not taken into consideration in this study, differential fish catchability with moon phase has been observed in the tropical Atlantic (Noguez Fuentes et al. 2007; Hernandez-Milian et al. 2008), presumably because the increased moonlight allows for easier prey location than at other moon phases (Bigelow et al. 1999). Fishers that target swordfish usually set during the evening with lightsticks on the majority of hooks (Witzell 1999) to mimic moonlight and to take advantage of swordfish nocturnal surface activity (Carey and Robison 1981; Luckhurst 2007). Longline fishing near the full moon was found to attract other visual predators, such as seabirds, and increase the likelihood of bycatch (Brothers et al. 1999; Gandini and Frere 2006). Sea turtles are also visual predators, have been caught during both the day and night (Watson et al. 2004; Báez et al. 2007), found to orient towards lightsticks (Wang et al. 2007), and were reported to be caught more frequently on hooks with lightsticks than on hooks without lights (Laurent et al. 2001). These behaviors make it likely that an increased attraction rate during the full moon may apply to sea turtles as well (Witzell 1999), explaining for the higher bycatch rates with more moonlight.

One regional exception for the lunar trend, found in the Northeast Distant, should be noted based on the high proportion of sea turtles caught in this region compared with the entire US pelagic longline fishery. A small, yet significant negative relationship of overall sea turtle bycatch and loggerhead sea turtle bycatch with moon illumination seems to indicate that sea turtle behavior in relationship to moon phase and fishing gear may be different or fishing practices may differ in the Northeast Distant compared with other northwestern Atlantic regions. Unlike the other fishing regions that have a more mixed target composition, the fishery in the Northeast Distant has traditionally focused almost exclusively on swordfish. As a result, gear configuration in this region, based on the US longline logbook data, differed from that in other regions, with lightsticks being used more in the Northeast Distant (mean = 707 per set) than in other regions (mean = 217 per set). In addition, set depth was shallower in the Northeast Distant (mean = 40 m) than in any other region (mean = 81 m). Fishing at shallow depths at night with a large number of lightsticks may counteract any effect of the moon phase on sea turtle catchability. However, without better knowledge of sea turtle behavior and vertical distribution in relation to moon phase, it is difficult to draw firm conclusions.

Comparing annual and lunar time scales

Seasonal and moon phase periods were both seen as important factors for explaining fishing success for regions, with season being the primary predictor having the strongest peaks in the spectral analysis and most often being the original node in the regression tree. Mackinson (2001) reported that local knowledge on combined factors (i.e., weather, moon phase, time of day, and season) was used for predicting catchability and abundance of seine fish, with maturation stage/season seeming to be the most important. Although weather and other environmental factors were not studied here, previous studies have found that lunar phase was a relatively small contributor to fish catch rates compared with environmental conditions, while date was reported as a strong predictor (see Ortega-Garcia et al. 2008). Furthermore, other effects on longline catch rates (i.e., vessel size, set depth, and species population trends; Ward 2008) could vary interannually, seasonally, or with lunar phase and were not taken into account here. Currently, trends in target catch and bycatch standardized by the combination of effects on longline fishing efficiency over time from all of the different environmental conditions, seasonal components, and fishing gear practices have yet to be assessed.

General implications for management

Although sea turtle bycatch is one of the major concerns in the management of protected species in pelagic longline fisheries, the current lack of ability to predict potential periods of high bycatch has limited the effectiveness of mitigation through the use of time-specific management measures. Periods of high sea turtle bycatch are a concern for fisheries and conservation, and the stability of high bycatch rates at a predictable time provides more compelling evidence to justify time-based mitigation measures. When high bycatch rates are not variable from year to year, this evidence of temporally stable high bycatch rates would be a strong case for time–area management measures. The presence of periodicity in catch and bycatch for certain regions shows that temporal patterns in the longline fishery are predictable on seasonal and lunar time scales, therefore helping fishers to anticipate time frames for abundant catch (maximize yield) and managers to anticipate times that would benefit most from bycatch mitigation (minimize cost). Since leatherback and loggerhead bycatch rates reported in large fishing regions showed different degrees of interannual variability, static time–area restrictions to reduce sea turtle interactions are feasible and their effectiveness would be maximized during months with high bycatch rates and low interannual variability.

On the other hand, results showing periods of high bycatch and high interannual variability, due to greater variation in oceanographic conditions, suggest that, in certain regions and seasons, dynamic time–area restrictions may be more suitable for reducing bycatch. Dynamic time–area closures for fixed fishing gear based on sightings of protected species are currently in place to protect Atlantic right whales (National Marine Fisheries Service 2002), although it is a costly way of predicting high rates of bycatch. A dynamic restriction based on oceanographic conditions (i.e., SST or chlorophyll *a* concentrations) that drive prey and zooplankton productivity and sea turtle distributions is an alternative strategy that could utilize information readily available from satellites to predict high sea turtle bycatch. Howell et al. (2008) found that bycatch was reduced following recommendations for avoiding longline fishing in areas of potentially high loggerhead sea turtle bycatch in the Pacific based on the relationship of bycatch and a frontal zone with high convergence and 18 °C isotherm. Much information has been recently obtained for sea turtle pelagic habitat preferences and seasonal migratory patterns (Godley et al. 2008), but more research is needed to model specific oceanographic or environmental conditions that also favor high bycatch rates in the Atlantic.

Based on the results of this study, possible time–area bycatch mitigation during the full moon would have a relatively low impact on yellowfin tuna catch in the Gulf of Mexico and Tuna North regions where yellowfin tuna is the main target species. However, these two regions also have had the most strongly positive correlations between swordfish catch and lunar illumination. Therefore, the cost of reducing effort and subsequently swordfish catch at the full moon may not outweigh the benefits of reduced bycatch, especially as the Tuna North region showed a significant increase in the number of hooks (effort) with fullness of the moon. Most regions showed this significant differential effort with moon phase, suggesting the possibility of fishers shifting target species along with moon phase in that fishers increased efforts to target swordfish during the full moon while shifting effort to yellowfin tuna during the new moon (i.e., timed departure and returns, changed gear configuration, time of fishing, type of bait, etc.). Beerkircher et al. (2009) noted that this “mixed target strategy” was used in the Gulf of Mexico and enabled fishers to increase swordfish catch rates while continuing to catch yellowfin tuna. He et al. (1997) also found that a larger percentage of swordfish sets in the Hawaii-based longline fishery were set during the full moon when compared with tuna sets. Since yellowfin tuna feed during the day (Grudinin 1989), longline sets targeting yellowfin tuna usually occur during the day without the use of lightsticks so the influence of the moon phase for light is reduced. In regions and fisheries outside the Atlantic Ocean, yellowfin tuna catch has been found either to not correlate with moon phase (Nishida 1995; He et al. 1997) or to be higher during the new and first quarter moons (Lowry et al. 2007). For the US Atlantic longline fishing fleet, most regions did display an increased yellowfin tuna catch rate with lunar illumination. Currently, there are no US longline fishing regulations based on moon phase, but closures around the full moon have been in place in Western Australia to protect species during periods of spawning and high catchability (Bowen and Hancock 1984; Phillips et al. 2007). More research on the relative effects of moon phase catchability and actively switching target species is required to warrant moon phase fishing regulations for the US Atlantic longline fishery.

Future time–area restrictions for mitigating sea turtle bycatch, either static or based on dynamic conditions, should take into account the predictable patterns found here to efficiently minimize both bycatch and impact on target catch rates. As such, distributions of foraging and spawning/nesting, oceanographic and prey conditions, and the foraging behavior of species affected annual and lunar catch and bycatch rates. These findings provide insights into the susceptibility of target catch and bycatch, regional and temporal patterns of fishing effort, and potential guidance for resource management and conservation. A better understanding of the importance and interactions of these time periods versus other factors affecting rates is needed for each pelagic longline fishing region. In addition, temporal variability and patterns should be used to assess the impact of current time–area management strategies affecting the US pelagic longline fleet and other pelagic longline fisheries with similar species of concern.

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