# Novel use of hook timers to quantify changing catchability over soak time in longline surveys

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## Highlights

- Catch rate changes over soak time in static baited gear.
- A method to estimate change in catch rates over longline soak time is proposed.
- Variability of conversion factors was small when propagated to index of abundance.
- Each unit of sampling effort should not be treated equally.

## Abstract

Fishery-independent survey sampling programs frequently undergo changes in operational procedures, which have the capacity to alter the catchability coefficient, *q*. To preserve the continuity of the time series, changes in sampling protocol must be accounted for within the raw data. We used data from a long-standing shark longline survey as a case-study to demonstrate a method of estimating changing catch over variable soak times. Catches of longline sets with and without hook timers were modeled using generalized linear models (GLMs) to estimate catch conversion factors over varying soak times. Estimated conversion factors were used to correct the raw catch data, which were then analyzed with delta-lognormal GLMs to estimate indices of relative abundance. Uncertainty in conversion factor estimation was calculated via bootstrap resampling and propagated through to annual indices by correcting raw data using resampled conversion factors. Added variation introduced by implementation of correction factors was relatively small compared to the magnitude of the observation error of the resulting indices of relative abundance. In species where catch rate declined over soak time, the expected CPUE of shortened soak times increased relative to standard soak times. Contrarily, if catchability increased over soak time, expected CPUE decreased in shortened soak times. Thus, we showed that the predominant practice of treating each unit of sampling effort as equal in fixed, baited gear is not appropriate, and changes in soak time should be accounted for to preserve the longevity of the time series.

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## 1. Introduction

Fishery-independent surveys are designed to estimate species relative abundance through the assumption that catch-per-unit-effort (CPUE) is proportional to abundance (*N*) via the catchability coefficient (*q*), such that CPUE = *qN*. Because *q* changes with time, space, and fishing power, survey CPUE data are often standardized by the use of generalized linear and additive models (GLMs/GAMs) structured to include covariates hypothesized to explain variation in *q* (Maunder and Punt, 2004). When surveys undergo operational procedure modifications, such as the use of a new gear or changes in sampling protocol, correction factors must be developed and applied to historic data to preserve the longevity of time-series. Changes to survey operations can often affect catchability, and failure to account for those effects can lead to unreliable interpretations of CPUE data and target stock abundance.

Bottom longlines are static gear commonly used for surveys targeting large species such as sharks that may outswim mobile gear such as trawls and that are too large to be efficiently captured in gillnets. The Virginia Institute of Marine Science (VIMS) longline survey is a longstanding sampling program that targets various shark species inhabiting the lower Chesapeake Bay and mid-Atlantic Bight (Musick et al., 1993). The survey was initiated in 1973 and used primarily as a tool to collect requisite life history and ecological information on harvested shark populations. Consequently, soak times were not standardized until the mid-1990s when the emphasis of the program was augmented to provide survey data that could be used to estimate indices of relative abundance for incorporation into stock assessments (SEDAR, 2006; 2011; 2013). Standardized longline soak time for this survey is currently four hours. However, within the historical VIMS longline data set (defined herein as prior to 1995), soak times range from 0.5 to 19 hours.

Catch rates for static gears have been shown to vary as a function of soak time (Rotherham et al., 2006; Ward and Myers, 2007). Declining catch rate over the duration of a longline soak can sometimes be attributed to factors other than changes in abundance, including bait loss (deterioration, falling off hooks during sets, degradation of olfactory properties, removal by non-target species), escape of target species, predation of target species, and gear saturation (Grimes et al., 1982; High, 1980; Sigler, 2000; Ward et al., 2004). Longline CPUE are typically expressed as the number of individuals captured per *k* hooks per *h* hours of soak time ($k \times h$ hook-hours). However, catchability may change over time during a longline set, which calls into question the validity of treating each hour of effort the same. If catch rates decline over soak time, CPUE would be expected to decrease with increasing soak time. In other words, if catch rates do not proportionately increase with increasing soak time (i.e., catchability declines over soak time), estimated CPUE may be artificially deflated. For example, define $CPUE_1 = C_1 / (100 \text{ hooks} \times h_1)$, where $CPUE_1$ is calculated from an observed catch of $C_1$ obtained from $100 \times h_1$ hook-hours. Assuming abundance is constant and catchability declines with soak time, a doubling of soak time ($h_2 = 2 \times h_1$) without a corresponding doubling in catch (say $C_2 = 1.5 \times C_1$) will decrease estimated $CPUE_2$ such that $CPUE_2 = 0.75 \times CPUE_1$.

In association with declining catch rates, increased soak times and protracted time spent on hooks have been shown to increase at-vessel fish mortality (Diaz and Serafy, 2005; Erickson and Berkeley, 2008; Marshall et al., 2015; Morgan and Burgess, 2007; Morgan and Carlson, 2010; Poisson et al., 2010). Post-release mortality of sharks is also positively related to time spent on hooks (Marshall et al., 2015). While it is apparent that decreasing soak times would decrease capture-related fish mortality, additional studies have suggested the existence of an optimal soak time that maximizes catch and replicability, while minimizing target and bycatch mortality (Erickson and Berkeley, 2008; Marshall et al., 2015; Rotherham et al., 2006). In an effort to quantify mortality rates of sharks caught using bottom longlines in Virginia waters, Marshall et al. (2015) noted that there exists a threshold soak time at three hours, after which total (at-vessel and post-release) mortality increases. By limiting soak times to less than three hours, total mortality would be reduced by approximately 46% in sandbar sharks (*Carcharhinus plumbeus*) and 60% in dusky sharks (*C. obscurus*; Marshall et al., 2015), two species commonly sampled by the VIMS longline survey.

Not only is the risk of increased mortality of sharks intrinsically harmful, it is particularly damaging given the population declines that several shark species experienced in the 1980s (Cortés, 2002; Musick et al., 1993; Musick et al., 2000; Peterson et al., 2017). Out of the seven most common species captured by the VIMS longline survey, one is listed on the IUCN Red List (IUCN, 2016) as least concern (Atlantic sharpnose shark, *Rhizoprionodon terraenovae*), three are near threatened (blacktip shark, *Carcharhinus limbatus*; spinner shark, *C. brevipinna*; tiger shark, *Galeocerdo cuvier*), and three are listed as vulnerable and currently are prohibited from commercial and recreational harvest (sandbar shark; dusky shark; sand tiger shark, *Carcharias taurus*). Further, given the capacity of the VIMS longline to interact with additional endangered and threatened species (e.g., sea turtles, several threatened shark species), effort has recently been directed at better understanding the distribution of capture times during survey operations. Data on time-at-capture can aid in optimization of field protocols and provide an analytical foundation for understanding the relationship between soak time and relative abundance.

Physical event timers, or hook timers, are extremely useful and informative tools for longline surveys. Historically, hook timers have been used to assess feeding time (Young et al., 2010), stress physiology (Brooks et al., 2012), and at-vessel (Berkeley and Edwards, 1998; Marshall et al., 2012; Morgan and Carlson, 2010) and post-release mortality due to extended hook time (Marshall et al., 2015) in an effort to minimize bycatch and target species mortality. In the current study, we utilize hook timers in a novel way to quantify and correct for changing catchability over soak time. With the use of hook timers, we present a methodology that can be used to generate correction factors for converting expected longline catches among differing levels of effort (soak times). The VIMS longline dataset will serve as a case-study to demonstrate the approach and convert total shark catch obtained from non-standard sets (soak times ≠ 4 hrs) to expected catch in a standard set (soak time = 4 hrs). While several catch comparison studies have previously been conducted (e.g., Benoît and Swain, 2003; Casey and Myers, 1998; Holst and Revill, 2009; Maki et al., 2006), few account for the increased uncertainty generated by applying correcting factors (Miller, 2013). We propose a method for uncertainty propagation, and characterize the effect of standardizing catch on resulting VIMS longline annual indices of abundance and corresponding coefficients of variation (CVs). Secondarily, in addition to converting catch to what would be expected in a standard four-hour set, we also investigated the effect of assuming a shortened standard set, defined as two hours.

## 2. Materials and Methods

### *2.1 VIMS longline survey*

The VIMS longline survey is a fishery-independent sampling program that targets large and small coastal sharks in the lower Chesapeake Bay and coastal waters of Virginia using bottom longline gear. A fixed station survey design is implemented, in which one or two longlines are set for four hours within six standard sampling areas annually primarily during the months of June-September (Fig. 1). Each set consists of approximately 2400 m of 4.8 mm diameter tarred, braided nylon mainline, with 100 equally spaced gangions. Each gangion is constructed of two meters of 4.8 mm diameter tarred, braided nylon mainline attached via an 8/0 barrel swivel to one meter of 1.6 mm diameter stainless steel leader, terminating with a 9/0 Mustad J hook (model 7698B DT). Gangions are fastened to the mainline via an 8/0 stainless steel longline snap. Norwegian buoys are placed between every 20 gangions, and each end of the mainline is anchored. Atlantic menhaden (*Brevoortia tyrannus*) has been used as standard bait since 1998, before which bait was selected opportunistically. Soak time, which is calculated as start of set to start of haul back, range from 0.5 to 19 hours in the historical data set, and were standardized to four hours in the mid-1990s (Fig. 2). While this method of soak time calculation has been disputed (Carruthers et al., 2011), sufficient data to define soak time differently are not available in the historical dataset, thus requiring the above soak time definition for consistency. Survey CPUE is defined as number of sharks captured per 100 hooks per hour (100 hook-hours) and data from the following species were analyzed: Atlantic sharpnose shark, sandbar shark, tiger shark, and sand tiger shark. All protocols pertaining to fish sampling were approved by the College of William & Mary's Institutional Animal Care and Use Committee (IACUC-2013-07-15-8812-jxgart).

*2.2. Hook timers*

Starting in 2014, VIMS longline survey gear was equipped with hook timers (Lindgren-Pitman® HT-600), timing devices that are activated when a fish pulls the gangion with sufficient force. By recording the time at which the set began and at which a fish was retrieved, the time that the fish triggered the hook timer can be determined, assuming that the trigger time accurately reflects the moment at which the fish was hooked. Hook timer data analyzed in this study were collected during survey years 2014-2016. Sampling areas at which hook timers were implemented were determined randomly prior to each monthly research cruise.

In the historical VIMS longline survey data set, 24% of longline sets experienced soak time exceeding four hours (48% of soak times were four hours). As such, it was necessary to convert the expected catch of longer sets to that of a standard longline set to generate indices of relative abundance that were corrected for non-standard soak time. Thus, in 2015 and 2016, ‘long’ sets outfitted with hook timers were conducted, where soak times were defined as at least 10 hours and sampling was conducted across day and night in an effort to mimic the structure of the historical data.

Out of 28 total longline sets conducted in 2014, a total of 14 were equipped with hook timers (four sets per month, sampling each standard sampling area two to four times). In 2015, hook timers were used on 21 out of 28 total standard longline sets. Additionally, seven ‘long’ day sets and seven ‘long’ overnight sets were conducted, evenly representing each month and sampling area. In 2016, 28 standard, four-hour sets were conducted, 26 of which were outfitted with hook timers, and six ‘long’ day and seven ‘long’ overnight sets were conducted.

*2.3 Statistical analyses*

*2.3.1 Statistical analyses: conversion factors*

Generalized linear and additive models can be used to partition or explain sources of variation in an attempt to summarize the relationship between one or several independent variables and a response variable whose distribution is part of the exponential family (McCullaugh and Nelder, 1989; Wood 2006). Given the categorical nature of covariates included in the current study, GLMs were used to estimate conversion factors between expected catch from different longline soak times. Because catch data were treated as counts, Poisson and negative binomial distributions were examined. However, preliminary analyses supported the utilization of negative binomial distribution (with a log link) due to overdispersion.

Expected catch of a non-standard soak time relative to a four-hour set was estimated with the following model:

$$\log(C_i) = \beta_0 + \beta_1(HT_i) + \beta_2(Y_i) + \beta_3(M_i) + \beta_4(S_i) + \varepsilon_i \quad (1)$$

where $C_i$ represents the catch of set *i* over a designated soak time (non-standard vs. standard), $HT_i$ is a binomial dummy variable indicating whether hook timers were utilized in set *i*, $Y_i$, $M_i$, and $S_i$ represent categorically defined year, month, and fixed sampling area of set *i*, respectively, and $\varepsilon_i$ is the associated error term. Different combinations of covariates were fitted, and Akaike's Information Criterion (AIC; Akaike, 1973) was used for model selection (Burnham and Anderson, 2002). When hook timers were used, the response variable was defined as the number of fish that tripped hook timers within the first *j* hour(s) ($j = 1, 2, \ldots, t_{max}$, where $t_{max}$ = 10+). When hook timers were not used, catch was measured as the total number of each species of interest captured over the full four-hour standard set. Thus, $\beta_1$ represents the proportion of fish hooked in *j* hour(s) relative to total catch over a standard four-hour set in log space, and $R_j = \exp(\beta_1)$ is the back-transformed estimated conversion. In an effort to avoid "double-counting" fish, correction factors were not based exclusively from longline sets on which hook timers were used, but instead were based on sets with hook timers compared to sets without hook timers.

If not all fish are able to activate the hook timers (e.g., small sharks), then the estimated proportion $R_j$ will be biased low. During field operations, fish were captured on inactivated hook timers (including broken tripped timers), which confirmed that hook timer efficiency was less than 100% in our study. Additionally, soak time in the VIMS longline was calculated as the start of set out to the start of haul back, such that several hooks of a set were fishing for longer than the corresponding calculated soak time, given that haul back requires more time to complete than set out. Consequently, an efficiency parameter, which encompasses hook timer failure, the potential for additional fish to be captured during haul back, and the potential difference between total catch on sets with and without hook timers, was estimated. This efficiency parameter was calculated from fitting the above GLM to catch data from fish hooked within four hours of soak time and standard sets without hook timers, where the parameter $E = \exp(\beta_1)$ now represents a "hook timer efficiency" or standardization parameter. The revised correction factor that accounts for hook timer efficiency ($CF_j$) was therefore calculated as: $CF_j = R_j / E$ (see Fig. 3). If all fish were capable of activating the hook timers, no fish were captured during haul back, and the catch of hook timer vs. non-hook timer sets were equal, there would be no difference in catch of a four-hour set with and without hook timers ($\beta_1$ = 0), and $E$ would be equal to one (e.g., $CF_j = R_j$). One thousand bootstrapped estimates of $CF_j$ were generated for each $j$ to estimate uncertainty, which was expressed as the 95% confidence interval (CI) calculated from the standard deviation of the conversion factors ($CI = CF_j \pm 1.96 \times \hat{\sigma}_{CF_j}$). All analyses were repeated to standardize soak lengths to the expected catch for a standard four-hour set as well as a shortened two-hour set.

*2.3.2 Statistical analyses: indices of relative abundance*

Estimated conversion factors were applied to adjust catches within the VIMS dataset. Because only conversions for hourly soak time intervals were calculated, data corrections were based on rounded soak times. Due to the large numbers of zero catch, species-specific indices of abundance were generated using delta-lognormal GLMs applied to the corrected data, in which presence/absence (PA) is fitted separately from positive, log-transformed CPUE (defined as catch per 100 hook-hours) data:

$$logit(\pi_i) = \beta_0 + \beta_1(Y_i) + \beta_2(M_i) + \beta_3(S_i) + \varepsilon_i$$

$$\log(CPUE_i) = \beta_0 + \beta_1(Y_i) + \beta_2(M_i) + \beta_3(S_i) + \varepsilon_i \quad (2)$$

where $Y_i$, $M_i$, $S_i$, and $\varepsilon_i$ are the same as in eq (1), $\pi_i$ represents the probability that the species of interest was captured on set $i$.

While equation (2) represents the fully saturated model parameterization, less complex models were also considered and model selection was based on AIC (Burnham and Anderson, 2002). Annual indices of abundance were estimated as the product of yearly predictions from each submodel based on marginal means (Searle et al., 1980). Predicted CPUE was back-transformed and bias corrected using the method described by Lo et al. (1992). Uncertainty estimates were expressed as annual variances and CVs, which were calculated via the equation $CV_y = \widehat{se_y}/\widehat{\mu_y}$, where $\widehat{\mu_y}$ represents the estimated mean index value in year *y*, and $\widehat{se_y}$ is the estimated standard error for that index value in year *y*. Corrected indices of abundance for all sharks species were generated for the entire VIMS longline time series relative to standard, four-hour set and shortened, two-hour sets.

*2.3.3 Statistical analyses: uncertainty propagation*

The conversion factors are estimated quantities and consequently are approximated within a range of uncertainty. Because the exact value is not known precisely, it is necessary to propagate the uncertainty surrounding the estimated conversion factor onto any predictions generated using said conversion. In the current study, we chose to propagate uncertainty using bootstrap resampling (Efron and Tibshirani, 1993), although other methods could have been utilized as well (e.g., Monte Carlo simulation).

The 1,000 sets of bootstrapped conversion factors were each used to generate a unique index of abundance, resulting in 1,000 four-hour converted indices and 1,000 two-hour converted indices. The resulting variation of these converted indices quantifies the magnitude of uncertainty introduced to the converted indices via implementation of the correction factors. The annual variance of these bootstrapped indices of abundance (representing the uncertainty resulting from correcting the raw data) was additively combined with the variance of the estimated indices (representing the uncertainty resulting from observation error, obtained from the delta-lognormal GLM using the delta method, Seber 1982) to generate total variance, similar to a two-stage sampling protocol, where numerical estimates of primary and secondary variances are added (Thompson, 2012). Because these two sources of variation are independent, total variance is the sum of each individual variance. Resulting variances and CVs for the corrected indices (calculated via additive variance) were compared to those of the standard, uncorrected index to compare the amount of variation added to the indices as a result of the conversion factors. All analyses were conducted in R version 3.1.1 (R Development Core Team, 2014).

## 3. Results

In the years 2014, 2015, and 2016, a fish was captured on 15.5% of all hooks deployed, within which 69.5% was comprised of sharks as opposed to teleosts, skates, and rays. Of the hooks retrieved that did not catch a fish, 52.5% were empty (no bait), 14.9% retained partial bait, and 32.7% maintained the whole bait throughout the set. Out of the 1250 sharks included in this analyses, 45 individuals were secondarily hooked (captured while preying on smaller sharks that were already hooked on the longline), and an additional 55 sharks were preyed upon while hooked. These fish subjected to predatory interactions were excluded from analyses, because there is no way of knowing whether the primarily or secondarily hooked fish tripped the hook timer. Consequently, 90 Atlantic sharpnose shark, three sandbar shark, and one spinner shark (*Carcharhinus brevipinna*) were primarily hooked, and 26 sandbar shark, six sand tiger shark, four blacktip shark (*C. limbatus*), and four tiger shark were secondarily hooked, all of which were subsequently excluded from analyses.

Species-specific histograms of hook-timer activation events showed clear differences in catch rates over soak duration, indicating unique catchabilities (Figs. 3 & 4). For example, while almost 60% of Atlantic sharpnose shark captured in four-hour sets were hooked within the first hour, less than 15% of tiger and dusky sharks were hooked within the first hour of soak time (Fig. 4). Based on the time-at-capture distributions, two-hours was chosen as a shortened soak time to ensure that sufficient numbers of all target species were captured, particularly those with low catch rates within the first hour (e.g., sandbar shark, tiger shark, and dusky shark).

*3.1 Conversion factors*

Prior to analyses, a negative binomial GLM was fitted to the total catch data (regardless of whether sharks tripped the hook timers), including the dummy variable for hook timer use. The corresponding coefficient to the binomial dummy variable was not statistically different from zero ($\beta$ = -0.153 ± SE 0.186; exp($\beta$) = 0.858; p=0.409). Consequently, we conclude that the total catch was not affected by the use of hook timers.

Due to the apparent species-specific differences in catch rate over soak time (Figs. 4 & 5), a complete set of conversion factors were generated for four species where sufficient data were available (Fig. 6). Results showed that Atlantic sharpnose sharks were predominantly captured in the first hour (45.8% ± SE 7% of the total catch in a four-hour set) and experienced a plateau effect after soak times of five hours, indicative of species-specific catch rates approaching zero (keeping in mind that the 10+ hour soak time bin represents a plus group). Sandbar sharks had a low catch rate in the first hour of soak time (15.3% ± SE 6% of the total catch in a four-hour set), and experienced an apparent plateau effect after six hours, where there was a statistical difference between the proportion of fish captured in seven hours through 10+ hours of soak time from what would be expected given constant catchability. The sand tiger shark showed a plateau effect after one hour of soak time, where there was no statistical difference in the proportion of sand tiger shark captured relative to four-hour sets in the second (88.5% ± SE 10%) through 10+ hours of soak time (105% ± SE 28%). In contrast, the tiger shark showed an apparent increase in catchability with longer soak times (catch in 10+ hours of soak time were 638% ± SE 184% relative to four-hour sets), although these correction factors were surrounded by large uncertainty. Conversion factors relative to a two-hour set showed similar trends with much greater variation (and hence, 95% confidence intervals; CIs) than those relative to a four-hour set (Figs. 6 & 7), likely due to less available data.

*3.2 Corrected indices of abundance with propagated uncertainty*

Bootstrapped conversion factors showed a considerable amount of uncertainty (Figs. 6 & 7). Nevertheless, the spread of resulting four-hour standardized indices generated from the bootstrapped correction factor values was relatively narrow, particularly later in the time series after soak times were standardized to four hours, as expected (Fig. 8). The variance associated with the two-hour converted indices was larger, reflecting the greater amount of uncertainty in the conversion factor point estimates. The spread of the 1,000 indices of abundance generated from the 1,000 bootstrapped sets of conversion factors for each species was larger when standardizing to two-hour longline soak times as compared to four-hour sets, reflecting the extra uncertainty in the sets of two-hour correction factors (Fig. 8). Given that soak times have been standardized to four hours in the latter part of the VIMS longline time series (since 1995), implementing correction factors for non-four-hour sets during this period had little effect on the four-hour corrected index of abundance relative to the unstandardized index of abundance (generated without use of correction factors by assuming that each unit of effort is equal) for all species examined. However, a slight divergence in four-hour corrected indices can be observed at the beginning of the time series for most species. Note that due to limitations associated with fitting delta-lognormal GLMs, several years of data in the historical time series were removed (i.e., years with all positive or negative observations of the species of interest, and years with less than three sets). Therefore, the cumulative effect of standardizing the historical time series was likely dampened.

The bootstrapped, two-hour corrected indices of relative abundance showed a much greater difference with respect to uncorrected indices than four-hour corrected indices. In the

Atlantic sharpnose shark, sandbar shark, and sand tiger shark, where catchability generally decreased with increasing soak time, two-hour corrected indices of abundance were greater in magnitude than four-hour corrected and uncorrected indices, which would be interpreted as increased CPUE. Contrarily, catchability generally increased with increasing soak time in the tiger shark, which showed slight decreases in the magnitude of two-hour corrected indices of abundance when compared to four-hour corrected and uncorrected indices (Fig. 8).

The resulting annual variance in the indices of abundance resulting from the use of correction factors was extremely small, especially when compared to the annual variance resulting from generating indices of abundance for all species (Table 1). On average, the mean annual variance attributed to correction factor utilization was two to three orders of magnitude (ranging from zero to three) smaller than the mean annual variance attributed to the observation error from the indices of abundance. The total variance of four-hour corrected indices was approximately equal to the variance of the uncorrected indices of relative abundance, while the total variance of the two-hour corrected indices was substantially larger than that of the uncorrected indices for all species excepting the tiger shark (Fig. 9). In the tiger shark, estimated variance associated with index observation error was similar for the four-hour and two-hour corrected indices compared uncorrected indices of abundance. However, annual coefficients of variation (CVs) associated with these indices of abundance were essentially equivalent for four-hour corrected, two-hour corrected, and uncorrected indices in the Atlantic sharpnose shark, sandbar shark, and sand tiger shark. This is likely because the increased variance was offset by the increased magnitude of the estimated yearly mean abundance. The two-hour corrected CVs were slightly larger in the tiger shark than the four-hour corrected and uncorrected CVs (Fig. 10). Survey indices are used as measures of relative abundance, such that the magnitude or scale of the index is not as important. Therefore, if the correction factors were simply scaling the uncorrected indices of abundance from year to year, correction factors utilization would be trivial, as long as we assumed a constant soak time. In our study, annual variability in soak time was sufficient to ensure that the cumulative effect of the correction factor was not constant over time. Moreover, the difference in the corrected versus uncorrected indices is proportional, such that greater relative abundance will undergo a larger change in magnitude when implementing correction factors (Fig. 11). As such, the magnitudes of increases or decreases in relative abundance are greater in a two-hour corrected index as opposed to an uncorrected index (e.g., Fig. 8).

As expected, by converting all catch to the expected catch over two-hour sets, more uncertainty was introduced to the indices than if the non-standard sets in the historical data set were converted to the expected catch over a standard, four-hour soak time. However, the added uncertainty resulting from the use of conversion factors was dwarfed by the magnitude of variance introduced from annual observation error (Table 1).

## 4. Discussion

Survey data are often standardized by applying GLMs or GAMs that contain covariates hypothesized to account for changes in catchability, $q$ (i.e., sampling site, month, depth, bottom type, etc.; Maunder and Punt, 2004). In some cases, conversion factors have been explicitly estimated to correct for changes in $q$ attributed to alterations in gear (e.g., Holst and Revill, 2009; Miller, 2013), sampling net material (e.g., Maki et al., 2006), and diel variability of target species (e.g., Benoît and Swain, 2003; Casey and Myers, 1998). However, despite knowledge of reduced bait efficiency over soak time of static gear (Grimes et al., 1982; High, 1980; Sigler, 2000; Ward and Myers, 2007) and hence, changes in catchability (Poisson et al., 2010; Rotherham et al., 2006; Ward et al., 2004), each temporal unit of sampling effort is typically treated as equal. The results of our study call into question the validity of this assumption, and we show that it is violated for the VIMS longline survey. Furthermore, while the estimation of conversion factors is important for proper inferences about sampled species, so is accounting for the additional uncertainty of implementing these correction factors (Holst and Revill, 2009). We have detailed a method to accommodate for uncertainty propagation of conversion factor utilization.

The results of our study clearly show that catchability of species within the VIMS longline is not constant over time, as demonstrated by the species-specific histograms of fish hooked over soak time. If catchability was constant over soak time, these histograms would show a uniform distribution of fish hooked over time. Nevertheless, when all species are pooled, it is apparent that catch rate, and therefore catchability, decreases over soak time.

If catchability was constant over time, a linear increase in correction factors over soak time would be expected. Specifically, relative to a four-hour set, we would expect the proportion of catch to increase based on a linear relationship with a slope of 0.25 and an intercept of zero. Hence, the expected catch in the first hour of soak time would be one quarter of that of a standard, four-hour set, half the standard catch would be expected in a two-hour set, and catch of a ten-hour set would be two and a half times that of a four-hour set. However, it is clear that, for three out of the four species analyzed in this study, catch plateaus with increasing soak time, indicating that the catchability approaches zero. For the tiger shark, predicted catch appears to be greater than what would be expected if catchability was constant over soak time, though not statistically significantly. Instead, it appears that the catchability of tiger shark increases with soak time in the VIMS longline. Therefore, for these species, defining CPUE according to arbitrarily chosen non-standard soak times would lead to biased indices of abundances.

We demonstrate the importance of implementing correction factors by supposing set time within the VIMS longline was shortened to a soak time of two hours starting in 2017 without correcting the historical data. Further assume that true abundance in 2017 was equal to 2016 abundance, and all other factors remained constant. A clear increase in CPUE would be observed for Atlantic sharpnose shark ($CPUE_{2016}$ = 1.28; $CPUE_{2017}$ = 2.13), sandbar shark ($CPUE_{2016}$ = 0.57; $CPUE_{2017}$ = 0.71), and sand tiger shark ($CPUE_{2016}$ = 0.03; $CPUE_{2017}$ = 0.06). In other words, more fish caught per effort would be landed in the shortened set conducted in 2017 compared to the standard, four-hour set conducted in 2016. Interpretation of these results would suggest that these shark species underwent a false increase in abundance from 2016 to 2017, while true abundance has not changed. For sharks that experience an apparent increase in catchability over soak time, like the tiger shark, we would infer a slight false decrease in abundance from 2016 to 2017 ($CPUE_{2016}$ = 0.07; $CPUE_{2017}$ = 0.06). This has clear implications with respect to monitoring programs that utilize static, baited gear. Without controlling for changes in soak time, interpreted abundance does not accurately reflect changes in actual abundance. As these fishery-independent data sets are critical to stock assessments (i.e., the VIMS longline is used in stock assessments for small and large coastal shark species; SEDAR 2006; 2011; 2013), these inaccuracies could be propagated through to impact assessment results and management recommendations. Note that these relationships only hold true when modeling CPUE as opposed to discrete catch with a Poisson or negative binomial distribution, using effort as an offset. Given the drastic differences in catchability over soak time and subsequent interpretation, the added uncertainty introduced by utilization of correction factors for systematic changes in soak time, it is extremely small relative to the magnitude of change of the index.

Inferences on rates of population increase and decline were also affected by soak time. When standardized to a two-hour soak time, estimated slopes of population change were magnified. For example, during the period of increase in the Atlantic sharpnose shark relative index of abundance (2003-2016), the slope of the increase estimated from a simple linear regression of the uncorrected index was 0.0753 ± SE 0.0193. The uncorrected index slope was comparable to the four-hour corrected relative index (0.0748 ± SE 0.0190). However, when corrected to a two-hour soak time, the slope of the increase was significantly greater (0.1214 ± SE 0.0291). These changes were likely further compounded in the historical data set, where correction factors had greater effects on corrected indices of relative abundance (e.g., sandbar shark population decline from 1977-1990).

The plateau effect of catchability with soak time is much more apparent in sand tiger shark relative to sandbar shark, and intermediate in Atlantic sharpnose shark, while it appears that catchability of tiger shark increases over soak time. It is clear that a single relationship between catchability and soak time does not hold for all species. When bait decomposes or falls off, the effective fishing time has expired for piscivorous coastal species. Hence, the asymptote of the catchability curve likely represents bait expiration. Specifically, sand tiger sharks are known to be relatively inactive (Smith et al., 2015), likely explaining their catch rate pattern, in which high catches rapidly resulted from setting the longline in the immediate vicinity of the species that appeared unwilling to travel longer distances to the baited lines. Larger coastal species such as the sandbar shark and tiger shark are known to consume small coastal elasmobranch species, including Atlantic sharpnose sharks (Ellis and Musick, 2007; Lowe et al., 1996), and they are commonly secondarily hooked by biting Atlantic sharpnose sharks or other small coastal elasmobranchs that have already been hooked (personal observation). This leads to the natural proposition that as smaller sharks are hooked, they become the struggling bait that attracts the larger predatory sharks, thereby increasing the effective fishing time (after survey bait has fallen off/decomposed/lost olfactory properties; Ward et al., 2004; Ward and Myers, 2007; Sigler, 2000) and potentially increasing the effective sampling area, or active space (as the bait decays and primarily hooked fish struggle, potentially bleed, and decompose, and the resulting auditory and chemical stimuli disperse) for larger, predatory sharks. This increase in sampling time/area is likely to increase the encounter rate of larger, more mobile and solitary individuals, such as the tiger shark (Randall, 1992).

Shortcomings to this approach include the possibility that the catchability curve (representing catch rate over soak time) changes over survey years, or with associated changes in environmental parameters (i.e. warming ocean temperatures). For example, Dixon et al. (2015) demonstrated that smooth dogfish (*Mustelus canis*) showed reduced feeding ability in waters treated with high concentrations of carbon dioxide (mimicking ocean acidification) due to decreased olfactory capacity. Naturally, any decrease in odor tracking capability would decrease sharks' ability to seek out bait on the longline, thereby decreasing catchability. Similarly, physical factors such as temperature, light, and current speed (Stoner, 2004) and biological factors such as prey availability (Bertrand et al., 2002) affect catchability of fish to baited fishing gear due to changes in feeding behavior. It has also been well established that local shark distributions (Conrath and Musick, 2008; Grubbs and Musick, 2005; Hoffmayer et al., 2014; Parsons and Hoffmayer, 2005) and, hence, shark CPUE (Bigelow et al., 1999; Brodziak and Walsh, 2013; Carlson, 1999; Hoey et al., 2002; Minami et al., 2007; Mitchell et al., 2014) change as a result of environmental conditions, indicating that these environmental factors may correspondingly affect the catchability curve. Analogous concerns can be attributed to the possibility that catch rate of each species changes at different fish densities. While this has not been investigated in sharks, several studies have shown a negative relationship between catch rate and teleost density (Angelsen and Olsen, 1987; Borgstrøm, 1992; Crecco and Overholtz, 1990). Alternatively, catch rates of fishes often increase with fish density in trawl gear (Godø et al. 1999), and other fish have been shown to seek out and attack baited hooks more quickly as a result of inter- and intraspecies competition within longlines (Løkkeborg et al., 2010; Stoner and Ottmar, 2004). While these are pertinent concerns, the same problems plague all gear or sampling method comparison studies. Given the drastic differences noted between expected catch of standardized four-hour sets and predicted catch in two-hour sets, it is likely a better choice to implement the corrections rather than ignore them, especially when accounting for added uncertainty.

By truncating the long sets to 10 hours, we functionally assumed that catch rate beyond 10 hours of soak time was effectively zero. Although this assumption was likely met for sand tiger shark analyses, it may not hold true for the other species analyzed. In the historical data set, only 5.6% of sets underwent soak times of longer than 10 hours. Due to limitations associated with fitting delta-lognormal GLMs, several years in the historical time series were removed from analysis, with the exact number varying by species. Consequently, the number of 10+ hour sampling events that were used to fit indices of relative abundance was further diminished (e.g., three 10+ hour sets included in sandbar shark index of relative abundance). Therefore, we conclude that the effect of implicating a plus group is negligible.

The results of this analysis of the VIMS longline data clearly demonstrate that each hour of sampling effort should not be viewed equally, which is the predominant practice in calculating CPUE of static sampling gears. For example, for any species within the historical VIMS longline data set, the catch of a 0.5 hour set is not directly comparable to the catch of a 19 hour set when standardized by effort (CPUE), as was previously assumed when calculating abundance. Although our results were specific to the VIMS longline, we present clear evidence that species-specific catch rate is variable with soak time on static gear as demonstrated in other studies (Rotherham et al., 2006; Ward et al., 2004; Ward and Myers, 2007), and we expect this trend holds true in other longline surveys. Ward et al. (2004) noted an example of the systematic bias that exists within commercial pelagic longlining data due to reduction in soak time since the initiation of the fishery. Importantly, we also present a method that could be used to investigate the effects of similar sampling modifications in the future while propagating uncertainty through to the level of index of relative abundance interpretation. Care should be taken in the future to minimize the effects of changing catchability with soak time, and we recommend additional experimentation in order to reduce biases that likely exist in several long-ranging time series.

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## Tables and Figure Captions

Table 1. Magnitudes of annual variance from generation of indices of relative abundance attributed to observation error (or base variation) versus the magnitude of uncertainty due to implementation of conversion factors (CFs) relative to standard, four-hour sets or shortened, two-hour sets.

Figure 1. The six standard, fixed stations from the VIMS longline, denoted by black dots. The VIMS longline survey samples coastal waters of Virginia, USA.

Figure 2. The historical soak times of VIMS longline sets. Boxes are denoted by the first and third quartile, while bold horizontal bars represent median soak times in each year. The widths of the boxes are proportional to the number of sets conducted in that year. The horizontal line superimposed at a soak time of four hours represents the current “standard” soak length.

Figure 3. Flow chart depicting calculation of two-hour conversion factor. Longline sets conducted with hook timers were used to identify times at which fish were hooked. Sets were coded with a binomial dummy variable to signify whether hook timers were utilized. To calculate the correction between the number of sharks that would be captured in two hours versus the number captured in a standard four-hour set, the number of sharks that tripped hook timers in the first two hours of soak time was regressed against the total number of fish caught in sets without hook timers. Though the coefficient associated with the binomial dummy variable should theoretically represent the conversion between the numbers of fish captured in a two-hour versus a four-hour set, we need to account for the fish that could not trip the hook timers, as well as other considerations detailed in the text. Hence, the “raw” two-hour conversion factor is standardized by the similar coefficient for the fish that tripped the hook timers in four hours versus the total number captured in four hours excluding hook timers. This ratio provided our estimated two-hour conversion factors.

Figure 4. Species-specific histograms displaying the time at which fish tripped hook timers during the longline soak. The total number of fish of each species that tripped the timers is given in parenthesis. The “All sharks” category represents all shark species pooled. Batoid and teleost species graphed in white are not of interest in the current study. Although representing the catch over standard, four-hour soak times, given the method in which soak time was calculated (beginning of set to beginning of haul), a fish could feasibly be hooked for longer than four hours given a particularly long haul back time. Note that the hammerhead species is displayed with a unique y-axis.

Figure 5. Experimental long sets (defined by soak times greater than or equal to 10 hours) were conducted in 2015 and 2016 with hook timers. These histograms display the density of individuals captured within each hour of soak time for each species. Note the unique y-axis for the hammerhead sharks.

Figure 6. Conversion factors generated relative to standard four- and two-hour soak times. The conversion factor at each hour can be interpreted as the proportion of fish that would be captured in four hours. Error bars represent the 95% confidence intervals. Note the scale of the y-axis is greater for the tiger shark.

Figure 7. Conversion factors generated relative to standard two-hour soak times. The conversion factor at each hour can be interpreted as the proportion of fish that would be captured in four hours. Error bars represent 95% confidence intervals. Note the scale of the y-axis is greater for the tiger shark.

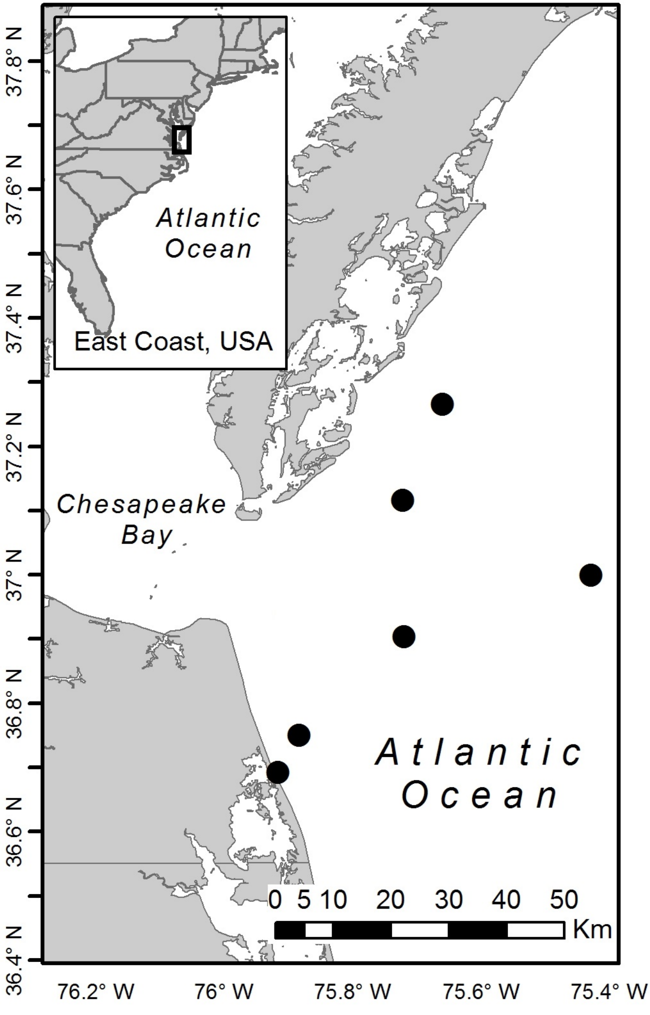
Figure 8. Delta-lognormal generalized linear model (GLM) based indices of relative abundance for Atlantic sharpnose shark, sandbar shark, tiger shark, and sand tiger shark. One thousand corrected indices of abundance were standardized to both four-hour sets and (shortened) two-hour sets from bootstrap resampled conversion factors (shown in light green and blue, respectively). Dark blue and green lines represent the four-hour and two-hour corrected indices of abundance calculated based on the point estimates of each conversion factor, respectively. The dashed black line represents uncorrected index of abundance calculated by assuming each hour of effort is equal. Note the unique y-axis for the tiger shark.

Figure 9. Total annual variance of uncorrected (dashed black line), four-hour corrected (solid green line), and two-hour corrected (solidi blue line) delta-lognormal generalized linear model generated indices of abundance for the Atlantic sharpnose shark, sandbar shark, tiger shark, and sand tiger shark. Note that the scale of the y-axes lower for the tiger shark and greater for the sand tiger shark.

Figure 10. Annual coefficients of variation (CVs) of uncorrected (dashed black line), four-hour corrected (solid green line), and two-hour corrected (solidi blue line) delta-lognormal generalized linear model generated indices of abundance for the Atlantic sharpnose shark, sandbar shark, tiger shark, and sand tiger shark.

Figure 11. Annual differences in corrected versus uncorrected indices calculated by subtracting the four-hour (blue) and two-hour (green) corrected indices of relative abundance from the uncorrected indices of abundance for the Atlantic sharpnose shark, sandbar shark, tiger shark, and sand tiger shark. Note the unique scale of the tiger shark y-axis. .

| | Standardized to four-hour sets | | Standardized to two-hour sets | |
|---|---|---|---|---|
| Species | Mean yearly variance associated index generation (Base variance) | Mean yearly variance associated with CF | Mean yearly variance associated with index generation (Base variance) | Mean yearly variance associated with CF |
| Atlantic sharpnose shark | 0.09327 | 0.00020 | 0.22987 | 0.01024 |
| Sandbar shark | 0.10493 | 0.00051 | 0.16794 | 0.01307 |
| Tiger shark | 0.00141 | 0.00004 | 0.00106 | 0.00024 |
| Sand tiger shark | 0.04614 | 0.00025 | 0.19782 | 0.00195 |


Atlantic
Ocean
East Coast, USA
Chesapeake
Bay
Atlantic
Ocean
0 5 10 20 30 40 50
Km
37.8° N
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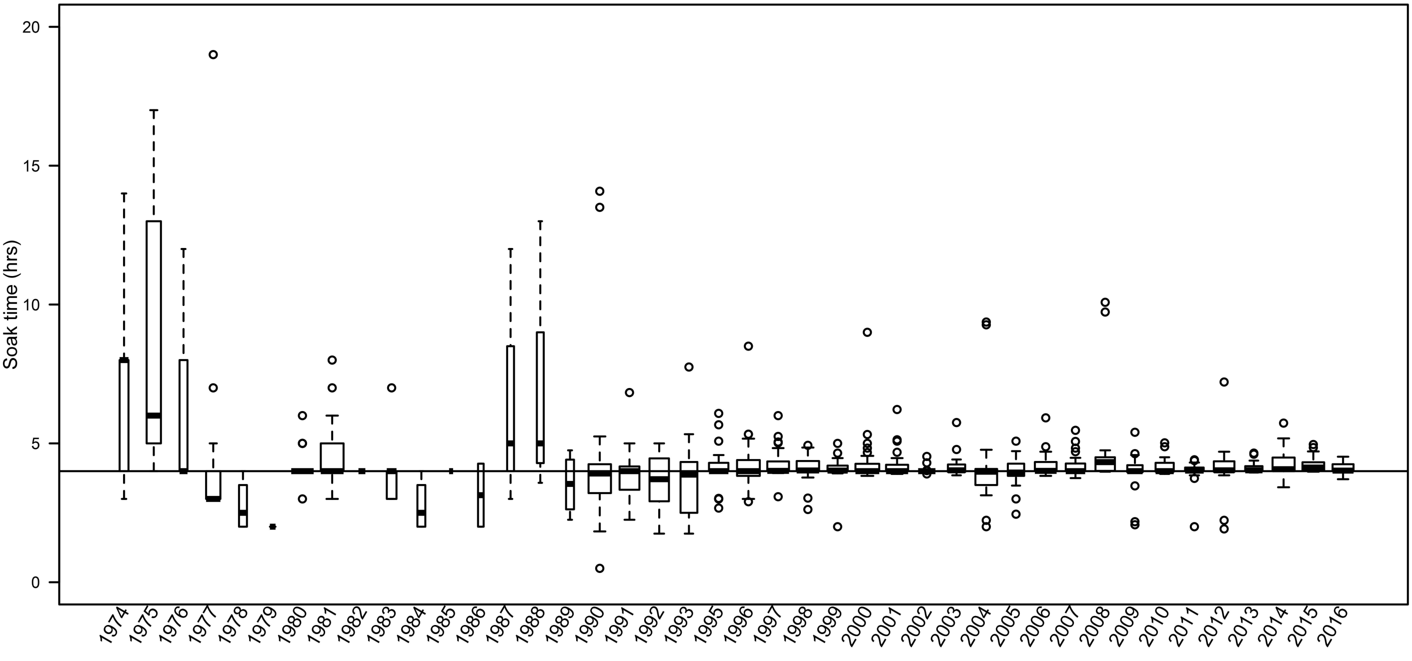
75.4° W



Soak time (hrs)
0
5
10
15
20
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
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1996
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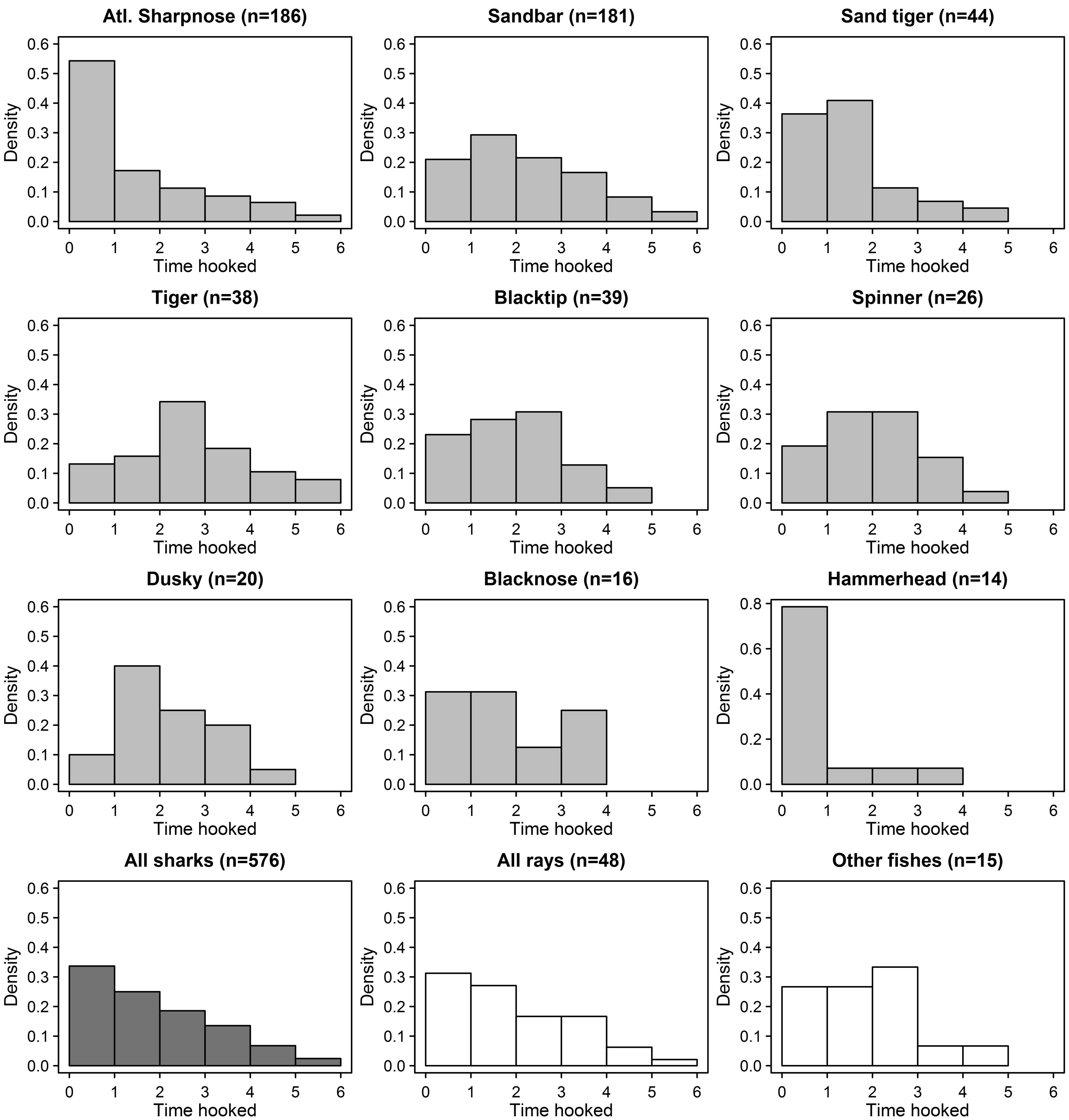
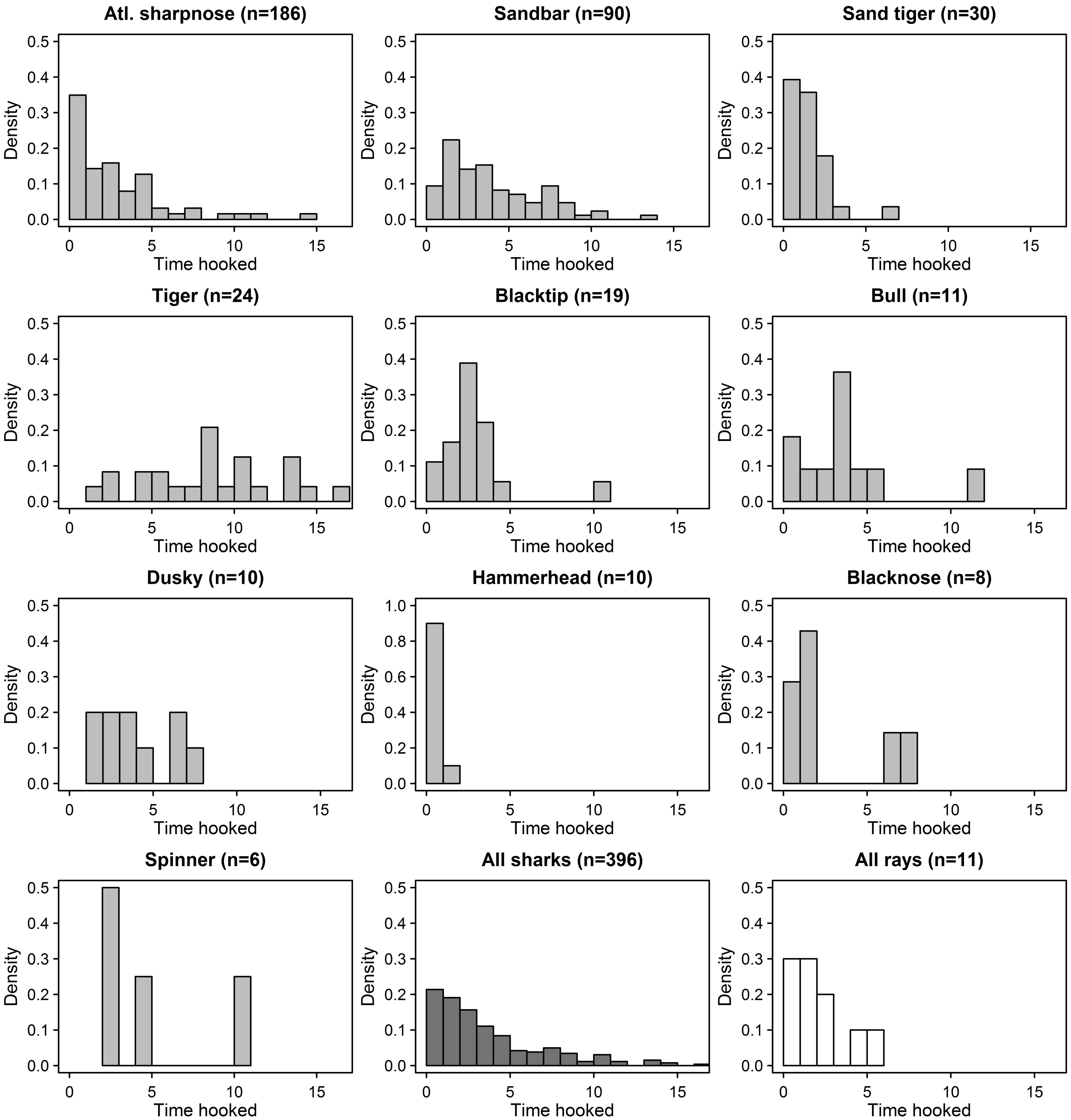
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016

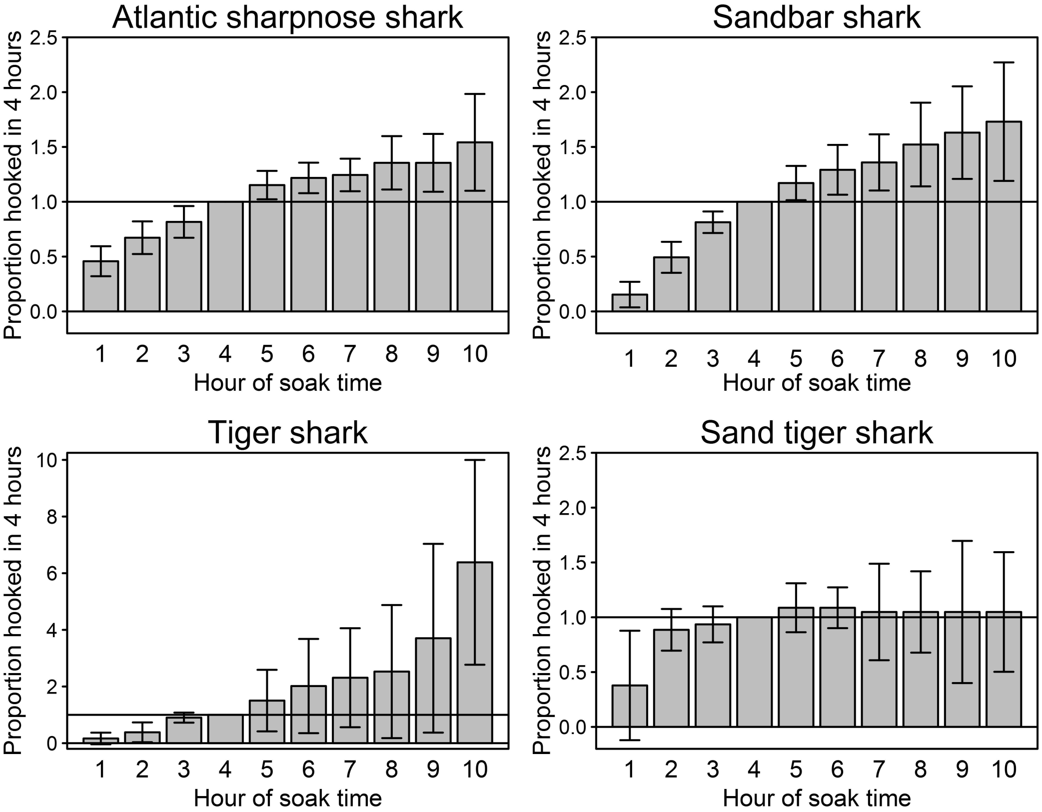

All 4-hour longline sets
Sets with hook timers
(Dummy variable 1)
Sets without hook timers
(Dummy variable 0)
Fish hooked in 1 hour
Fish hooked in 2 hour
Fish hooked in 3 hour
Fish hooked in 4 hour
Total fish caught
(in 4 hour soak)
GLM
Fish hooked in 2 hours
÷
Total fish caught
Raw 2-hour conversion
Fish hooked in 4 hours
÷
Total fish caught
GLM
=
Hook timer efficiency
=
Corrected 2-hour conversion factor



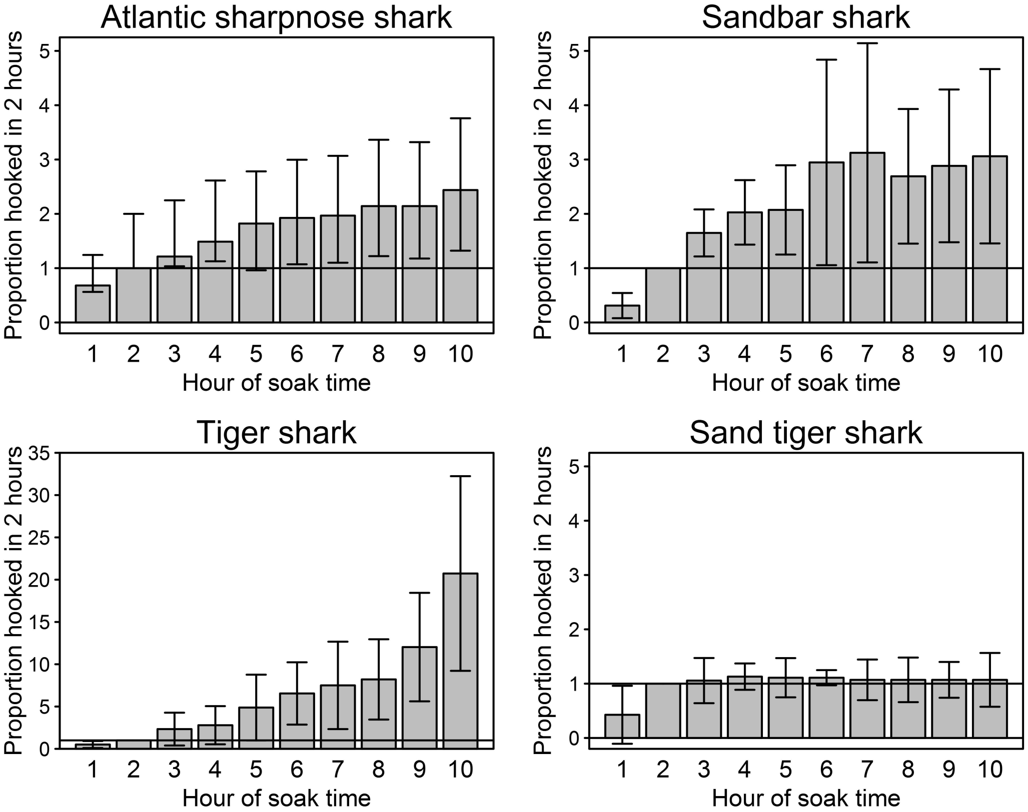
Atl. Sharpnose (n=186)
Sandbar (n=181)
Sand tiger (n=44)
Tiger (n=38)
Blacktip (n=39)
Spinner (n=26)
Dusky (n=20)
Blacknose (n=16)
Hammerhead (n=14)
All sharks (n=576)
All rays (n=48)
Other fishes (n=15)
Density
Time hooked

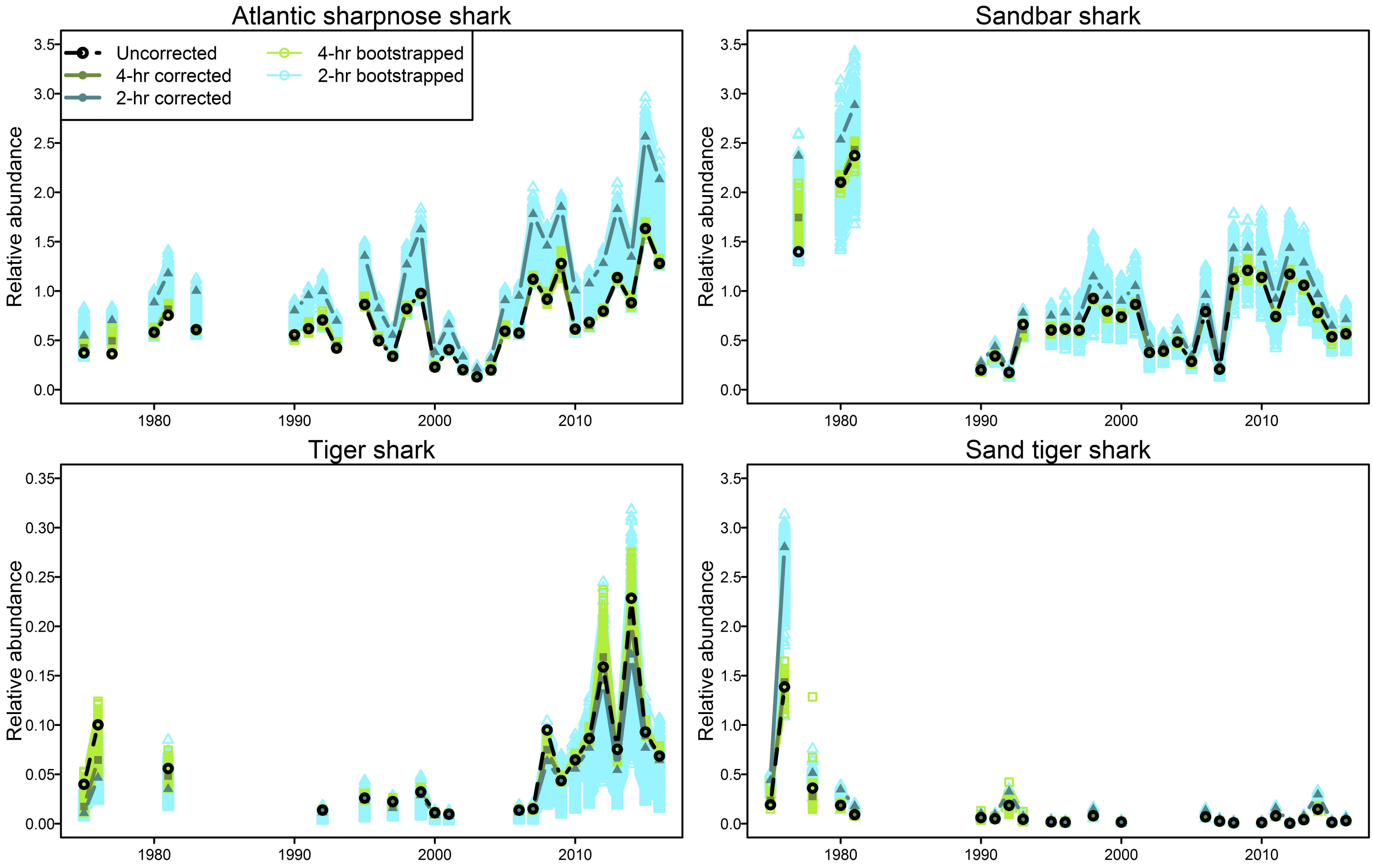


Atl. sharpnose (n=186)
Sandbar (n=90)
Sand tiger (n=30)
Tiger (n=24)
Blacktip (n=19)
Bull (n=11)
Dusky (n=10)
Hammerhead (n=10)
Blacknose (n=8)
Spinner (n=6)
All sharks (n=396)
All rays (n=11)
Density
Time hooked

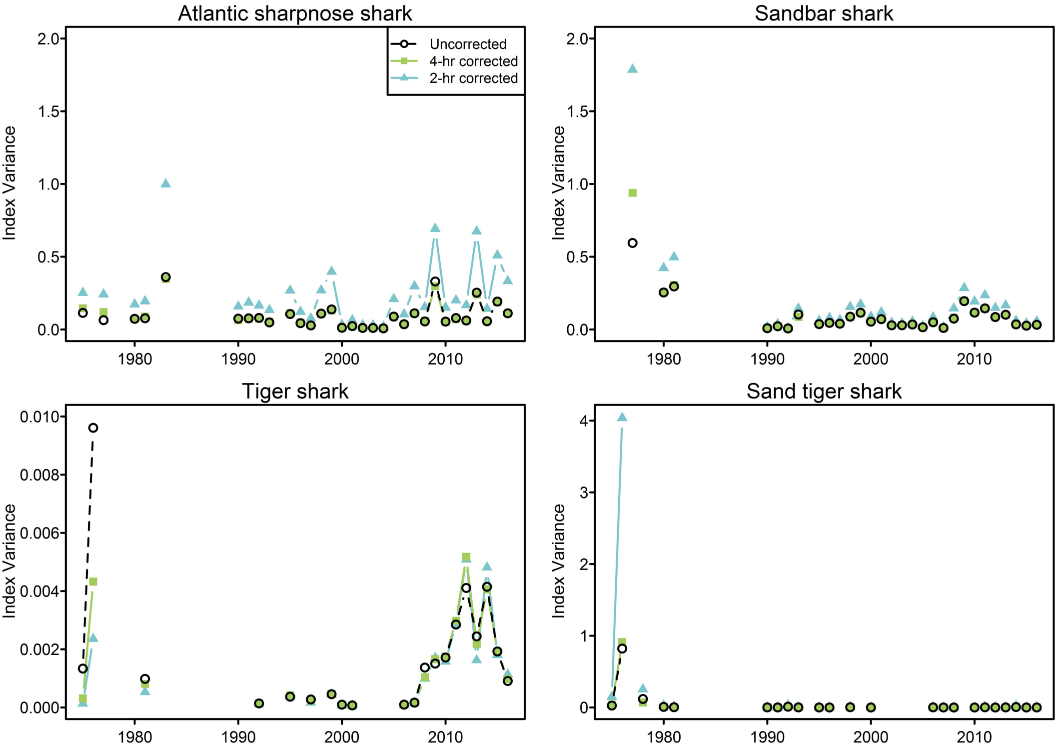


Atlantic sharpnose shark
Sandbar shark
Tiger shark
Sand tiger shark
Proportion hooked in 4 hours
Hour of soak time
0.0
0.5
1.0
1.5
2.0
2.5
0
2
4
6
8
10
1
2
3
4
5
6
7
8
9
10

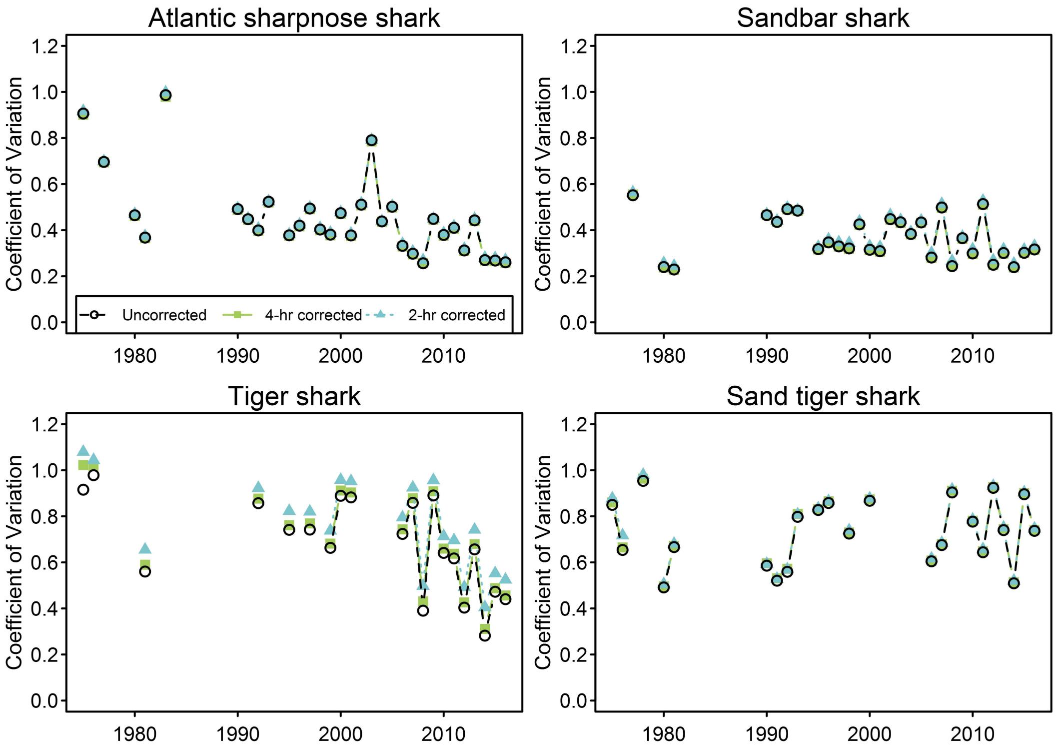

Atlantic sharpnose shark
Sandbar shark
Tiger shark
Sand tiger shark
Proportion hooked in 2 hours
Hour of soak time
0
1
2
3
4
5
5
10
15
20
25
30
35
6
7
8
9
10

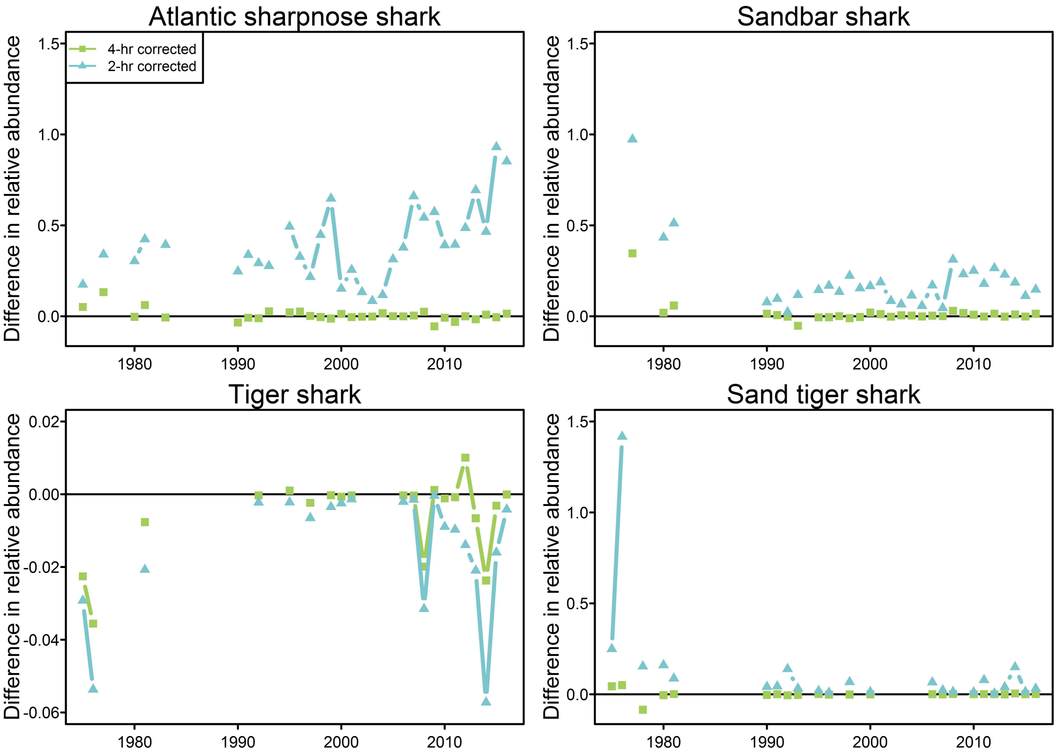


Atlantic sharpnose shark
Sandbar shark
Tiger shark
Sand tiger shark
Uncorrected
4-hr corrected
2-hr corrected
4-hr bootstrapped
2-hr bootstrapped
Relative abundance
1980
1990
2000
2010



Atlantic sharpnose shark
Uncorrected
4-hr corrected
2-hr corrected
Index Variance
2.0
1.5
1.0
0.5
0.0
1980
1990
2000
2010
Sandbar shark
Index Variance
Tiger shark
Index Variance
0.010
0.008
0.006
0.004
0.002
0.000
Sand tiger shark
Index Variance
4
3
2
1
0


Atlantic sharpnose shark
Sandbar shark
Tiger shark
Sand tiger shark
Coefficient of Variation
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1980
1990
2000
2010
Uncorrected
4-hr corrected
2-hr corrected



Atlantic sharpnose shark
Sandbar shark
Tiger shark
Sand tiger shark
4-hr corrected
2-hr corrected
Difference in relative abundance
1.5
1.0
0.5
0.0
0.02
0.00
-0.02
-0.04
-0.06
1980
1990
2000
2010