Use of pop-up satellite archival tag technology to study postrelease survival and habitat utilization of estuarine and coastal fishes: an application to striped bass (*Morone saxatilis*)

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Abstract:

Pop-up satellite archival tags (PSATs) have been used to study movements, habitat utilization, and postrelease survival of large pelagic vertebrates, but the size of these tags has historically precluded their use on smaller coastal species. To evaluate the utility of a new generation of smaller PSATs to study postrelease survival and habitat utilization of coastal species, we attached Microwave Telemetry, Inc., X-Tags to ten striped bass (*Morone saxatilis*) 94 -112 cm total length (TL) caught on J hooks and circle hooks during the winter recreational fishery in Virginia. Tags collected temperature and depth information every five minutes and released from the fish after 30 days. Nine of the ten tags released on schedule and eight transmitted 30% to 96% (mean 78.6%) of the archived data. Three tags were physically recovered during or after the transmission period, allowing retrieval of all archived data. All eight striped bass whose tags transmitted data survived for 30 days following release, including two fish that were hooked deeply with J hooks. The eight fish spent more than 90% of their time at depths less than10 m and in temperatures of 6-9°C, demonstrated no significant diel differences in depth or temperature utilization ($P > 0.05$), and exhibited weak periodicities in vertical movements consistent with daily and tidal cycles.

Developments in pop-up satellite archival tags (PSATs) have greatly improved scientific understanding of the postrelease survival, behavior, and movements of marine vertebrates – animals from which it is not always practical to physically recover tags to obtain data (Arnold and Dewar, 2001; Graves et. al. 2002). PSATs take physical measurements (e.g., temperature, pressure, light level) while attached to study animals, independently detach at predetermined times, float to the surface, and transmit data to orbiting satellites of the Argos system. Owing to the mass and size of older tags (~65 g), PSAT deployments have historically been limited to large pelagic marine vertebrates such as billfishes, tunas, sharks, and sea turtles. Recent miniaturization of tag components has led to the development of a new generation of PSATs that are 33% smaller, thus enabling the collection of high resolution time-series data for inferences regarding short-term fate and habitat utilization of increasingly smaller species, including many estuarine and coastal fishes.

To evaluate the utility of the new generation of smaller PSATs for studies of estuarine and coastal fishes, we deployed ten tags on large, coastal, migratory, striped bass (*Morone saxatilis*) caught on live baits rigged on two hook types in the winter recreational fishery off coastal Virginia and North Carolina. While smaller PSATs provide opportunities to investigate smaller species, coastal and estuarine fishes and the characteristics of their habitats present special challenges for PSAT deployments. First, many coastal species associate with physical habitat structures in which the tags could become entangled, possibly resulting in premature release. Secondly, many coastal species aggregate, providing opportunities for conspecifics or other species to interact with the tag, possibly causing premature release or damage to the PSAT. Finally, because coastal species occur near shore, there is an increased probability that a released (transmitting) PSAT will wash ashore during the transmission period, potentially reducing the quality and quantity of subsequent data transmissions. On the other hand, the increased probability of beaching during data transmission may provide researchers opportunities for directed tag recovery.

A second goal of this study was to gain insights into the post-release survival of striped bass released from recreational fishing gear during the winter prespawning aggregation near the mouth of Chesapeake Bay. Striped bass are a highly prized recreational gamefish, providing over $300 million to the U.S. economy and over $60 million to Virginia annually (Kirkley and Kerstetter, 1997; Richards and Rago, 1999). Management regulations such as seasonal bag and size limits have resulted in the release of over 90% of the striped bass caught by recreational anglers (Van Winkle et al., 1988). Current recreational postrelease mortality estimates for striped bass range between 3% and 67%, and a value of 9% is currently used in population assessments for the Chesapeake Bay stock (Diodati and Richards, 1996). However, previous studies have generally been conducted in fisheries and environmental conditions very different from those near the mouth of Chesapeake Bay during the winter months (Table 1).

A third goal of this study was to elucidate the habitat utilization of coastal migrant striped bass during the winter prespawn aggregation in the coastal sea along Virginia. The habitat use of juvenile striped bass within estuarine and riverine waters has been fairly well studied (Tupper and Able, 2000; McGrath, 2005), as have the movements of adults during upriver spawning migrations (Carmichael et al., 1998). Little is known about the depth and temperature utilization or short-term movements of adult striped bass in winter prespawning aggregations along the U.S. Mid-Atlantic coast, despite the importance of Chesapeake Bay to the coastal migrant population. The Chesapeake Bay stock is thought to be the most productive along the Atlantic coast, serving as a major source of coastal recruits and accounting for > 90% of Atlantic coastwide landings in some years (Kohlenstein, 1981; Richards and Rago, 1999; Secor, 2000). Identifying the habitat characteristics and utilization patterns of coastal migrant species in areas of aggregation are necessary for effective current and future management efforts (Carmichael et al., 1998; Conrath and Musick, 2008).

Materials and Methods

The X-Tag High Rate Archival Tag (X-Tag, Microwave Telemetry, Inc., Columbia, MD) used in this study is slightly buoyant, and weighs 40 g in air. The body of the tag contains a lithium composite battery, a microprocessor, a pressure sensor, a temperature gauge, a light sensor, and a transmitter, all encased within a carbon fiber housing. Flotation is provided by a spherical resin bulb embedded with buoyant glass beads and the tag can withstand pressure equivalent to a depth of 2500 m. This tag model was programmed to record and archive a continuous time-series of temperature, light, and pressure (depth) measurements approximately every five minutes for 30 days. The tags transmitted depth measurements at intervals of approximately 1.3 m and temperature in increments of 0.17°C. Not having prior information on the time course or range of vertical movements of striped bass overwintering off the mouth of Chesapeake Bay, we chose not to activate an optional feature that provides for early tag release in the case of a mortality which is inferred if the tag remains at constant depth (±1.5 m) for four days.

The X-Tags were equipped with Satellite in View™ technology that increases battery life and data recovery by restricting transmissions to times during which there is a high likelihood of an Argos satellite pass above the horizon.

Striking a balance between availability and size of striped bass in the winter recreational fishery off the mouth of Chesapeake Bay, we arbitrarily set a minimum length threshold for tagging of 94 cm total length (TL). Striped bass in this size range are sexually mature coastal migrants (Dorazio et al., 1994) that weigh 8 kg or more (Secor, 2000) and were considered to be of sufficient size to carry the X-Tag.

Striped bass were caught using live eels (*Anguilla rostrata*) as bait on 13.6 kg test sportfishing tackle with 1.2 m leaders of 36.3 kg test line. Five striped bass were caught on J hooks (Gamakatsu Octopus, size 7/0, no offset), and five on circle hooks (Gamakatsu Octopus Circle, size 7/0, no offset). Fish were netted and brought on deck where the hook location was noted, the hook removed, total length measured, and the PSAT attached before the fish was returned to the water (air exposure time less than two minutes).

PSATs were attached to striped bass by an assembly composed of 16 cm of 182 kg test monofilament fishing line (Momoi Fishing Co., Ako City, Japan) attached to a large, hydroscopic, surgical grade nylon intramuscular tag anchor according to the method of Graves et al. (2002). Attachment assemblies were implanted with a 5-cm stainless steel applicator attached to a 0.3-m tagging pole that was inserted behind a scale approximately 5 cm deep into a target region approximately 6 cm posterior to the origin and 5 cm ventral to the base of the dorsal fin (Fig. 1). In this region, the nylon anchor can pass through and potentially interlock with pterygiophores supporting the dorsal fin well above the coelomic cavity containing visceral organs (Graves et al., 2002).

Data analyses

Net movement was calculated as a minimum straight line distance (MSLD) traveled between coordinates of initial tagging and coordinates of the first reliable satellite transmission using Argos location codes 1, 2, or 3 (Horodysky et al., 2007). Archived and transmitted point measurements of depth and temperature recorded by PSATs were summarized in 5 m and 1°C interval histograms. Datasets were truncated to remove records prior to tagging and after PSAT pop-up.

To assess potential diel differences in habitat utilization, mean depths and temperatures were generated for each diel period (day, night) of each tracking day (n = 30) for each of the eight striped bass. Diel period designations were based on times of local sunrise and sunset; crepuscular periods (30 minutes on either side of dawn and dusk) were eliminated from all diel analyses. Diel differences in the depth and temperature means were assessed separately with linear mixed effects models of the form (Pinheiro and Bates, 2004):

$$Y_{pi} = \mu + \tau_p + \alpha_i + \varepsilon_{pi}, \quad (1)$$

Where μ = the overall mean depth or temperature;

τ_p = the fixed effect of diel period p;

α_i = the random effect due to individual fish; and

ε_{pi} are error terms.

Application of linear models requires satisfying three assumptions: independence and normality of the response within and among samples, and homogeneity of variances among all levels of the fixed effects (Underwood, 2002). However, PSAT data constitute repeated non-independent observations within individual fish and may fail to satisfy the assumptions of normality and homogeneity of variance. Accordingly, a repeated measures form of Eq. 1, including a Box-Cox transformation of the depth and temperature data, rectified these issues in the striped bass data. To characterize the within-individual autocorrelation, several candidate covariance structures were fitted to the transformed depth and temperature data, and the appropriate structure was selected using Akaike's Information Criterion (*AIC*):

$$\mathrm{AIC} = -2\ln(\hat{L}) + 2p \,, \qquad (2)$$

where $\hat{L}$ = the estimated value of the likelihood function at its maximum; and

p = the number of estimated parameters (Burnham and Anderson, 2002).

We performed fast Fourier transform (FFT) analyses to assess any periodicities inherent in the time series of the three recovered tags for which 100% of the archived data were obtained. FFT approximates a function composed of sine and cosine terms from a time-series (Chatfield, 1996), and is particularly well suited to analyzing high-resolution datasets resulting from archival tagging studies (Graham et al., 2006; Shepard et al., 2006). The influence of periodic components in a time-series is indicated by the magnitude of the corresponding spectral peak in a periodigram (Shepard et al., 2006). Spectral components of fractional periodicities (i.e., part of a tidal cycle, moon phase, etc.) occurring before and after the tag deployment duration can interfere with each other, generating frequency peaks that do not represent meaningful behavioral periodicities (Shepard et al., 2006). We therefore applied a Hamming window to the depth records of each of the three striped bass to reduce the effects of such adjacent spectral components

(Oppenheim and Schafer, 1989). All statistical analyses were performed using the software package *R,* version 2.7.1 (R Development Core Team, 2008).

Results

Ten striped bass, ranging in size from 94 – 112 cm TL (mean = 96.5 cm), were caught on live eels rigged with circle or J hooks in coastal waters (<20 m depth) of Virginia and North Carolina during late January and early February 2008 (Table 2). Fight times ranged from 1 min 10 sec to 5 min 30 sec (mean = 2 min 16 sec). All five fish caught on circle hooks were hooked externally, either in the upper jaw or the corner of the jaw. Two of five fish caught on J hooks were hooked deeply and the other three were hooked externally. Hooks were removed from all fish before they were tagged and released.

Eight of the ten PSATs popped up on schedule and transmitted data that were received by satellites of the Argos system. A single, weak transmission was received from one of the two remaining tags on the day it was scheduled to release, and no transmissions were received from the other PSAT. The tags had sufficient battery power to transmit data for approximately 30 days, and during that time three of the eight reporting PSATs washed ashore. Two of these tags (fish 2 and 4) were physically recovered while transmitting. Transmissions from the third tag (fish 7) ceased when it washed ashore four days after surfacing; this tag was not recovered. A fourth tag (fish 8) remained adrift during its transmission period and subsequently washed ashore north of Cape Hatteras, NC, where it was recovered by a recreational angler.

Data recovery rates varied among the eight transmitting tags. All of the archived data were manually downloaded from the three tags that were recovered after washing ashore. For the four tags that remained adrift during the transmission period and not subsequently recovered (fish 1, 3, 5 and 6), data recovery rates were high, ranging from 87-96%. The PSAT from fish 7 surfaced just off the seaside of the Eastern Shore of Virginia and washed ashore on Parramore Island after four days at which time transmissions ceased to be received. During the four day transmission period, 30% of the archived data were recovered from this tag.

Based on visual inspection of depth and temperature data we inferred that all eight striped bass with reporting tags, including the two fish that were deeply hooked with J hooks, survived for 30 days following release. Each fish exhibited multiple vertical movements in the water column throughout the 30-day tagging period (Fig. 2). Inferences of survival based on depth and temperature data were also supported by calculations of net movement (Graves et al., 2002). Minimum straight line distances for the eight striped bass ranged from 12.6-58.6 nautical miles (nmi; 23.3 – 108.5 km), with a mean of 34.9 nmi (64.6 km; Fig 3). During the 30 day tagging period, three individuals (fish 2, 4 and 5) left coastal waters and entered Chesapeake Bay, presumably initiating spawning migration.

Depth and temperature data archived by the eight transmitting X-Tags demonstrated that coastal migrant striped bass spent >90% of their time in the upper 10 m of the water column in temperatures of 6-9°C (Fig 4). Two striped bass (fish 2 and 5) entered warm temperatures (~15°C) at approximately the same time on the same date. These individuals, tagged on different days in North Carolina waters, may have moved eastward to a warm core eddy confirmed by satellite temperature imagery for 7 February 2008 (http://marine.rutgers.edu/cool/sat_data). It is also possible that these fish instead moved into shallow coastal or estuarine waters warmed by unseasonable temperatures (~18ºC) on 7 February 2008.

Despite the daily variability in the tracks of individuals, repeated measures linear mixed effects models yielded no significant diel differences in striped bass depth or temperature utilization ($P>0.05$). The best fitting model for both depth and temperature data was the autoregressive moving average (ARMA) covariance structure.

Fast Fourier transform periodigrams of the three recovered tags revealed weak periodicities in vertical movements consistent with one cycle per day (i.e., 24 hours), and weaker behaviors consistent with two and three cycles per day (i.e., 12 and 8 hours, respectively; Fig. 5). All three periodigrams had large spectral peaks near zero, a consequence of standardizing the depth data by the average depth; main spectral components follow this initial clustering (Shepard et al., 2006). The main spectral components were identified both with and without the Hamming window, thus were not attributed to artifact. It is unclear if the periodicities of approximately 12 hours and 8 hours represent specific behavioral cycles or harmonics that result from non-sinusoidal behavior (Chatfield, 1996).

Discussion

The primary goal of this study was to evaluate the performance of a new generation of smaller PSATs on estuarine and coastal species in the nearshore environment. The larger, older models of PSATs have been deployed on coastal elasmobranchs (Grusha, 2005; Conrath and Musick, 2008). As comparatively smaller coastal and estuarine fishes become candidates for these smaller tags, researchers may wish to consider the minimum size at which drag and lift forces acting on the PSAT impact behavior and survival (Grusha and Patterson, 2005). Based on the movements of fish and lack of observed mortalities, we conclude that striped bass of ~1 m TL length appear to be of sufficient size to carry the X-Tag.

At the outset of this study we were concerned with the potential for premature release of PSATs due to entanglement in physical structure, fish-tag interactions that would result in premature release or tag damage, and the likelihood that tags would effectively transmit the archived data from nearshore waters. The lack of prematurely released tags in this study confirms that fouling or interactions with structure were not problematic for striped bass; however, the applicability of these results to other structure-associated species is not known. Premature release of PSATs has been noted in many studies and may become more prevalent with longer deployment times due to attachment methodology and increased potential for fish-tag interactions (Domeier et al., 2003; Conrath and Musick, 2008; Graves and Horodysky, 2008). The selection of a specific attachment methodology and an appropriate release time will depend on the species studied and research objectives of the study (e.g., postrelease mortality, movement, or habitat utilization).

Fish-tag interactions present challenges for all PSAT studies, and may occur as predation of a tag mistaken for a prey item or predation of an individual carrying a tag. Both outcomes are extremely difficult to quantify and compromise study objectives. In schooling piscivorous fishes such as adult striped bass, predation of PSATs is more likely than predation of study individuals. We cannot discount that our non-reporting and weakly transmitting tags may have been victims of tag predation; it is impossible to discern between tag predation and tag failure. However, it is unlikely that mortality of a tagged striped bass would result in a non-reporting tag, as the PSAT should surface from a dead carcass after 30 days. Previous studies have inferred predation of live individuals and scavenging of dead fish carrying PSATs by elasmobranchs (Kerstetter et al., 2004; Kerstetter and Graves, 2008). In these instances, the PSATs were not compromised during ingestion and successfully transmitted after regurgitation, but it is likely that damage during such events may be a cause of PSAT non-reportings.

The success of studies utilizing PSAT technology directly hinges upon on the quality and quantity of the archived data that are transmitted from the tag to the Argos satellite system. Reception of PSAT transmissions is maximized when the tag antenna is unobstructed and above the surface of the water in a vertical position. In our study, we obtained at least 90% of the data from tags that remained adrift for the entire data transmission period. There is an increased probability that tags attached to estuarine and coastal fishes will wash ashore during the transmission period that typically lasts about 30 days. Tags beach in a horizontal position which may result in decreased signal reception, especially if antennae are submerged in water or fouled with algae or other debris[1]. Beached tags in this study transmitted 30 – 90% of their data. In the case of tag attached to fish 7, which beached after only four days of transmission and ceased communicating with the satellite shortly thereafter, the transmission of over 3000 data points provided more than sufficient information to infer survival and investigate habitat utilization of that individual. The random transmission of data packets (nine consecutive time points) by the X-Tags during times when a satellite of the Argos system is likely

[1] P. Howey, 2009, Microwave Telemetry, Inc., 8835 Columbia 100 Parkway, Suites K & L, Columbia, MD 21045

above the horizon generally results in a rapid accumulation of data during the first week of the thirty day transmission period (Figure 6).

The two tags that were recovered while still transmitting (fish 2, 4) were carried by fish that moved from coastal waters into the mainstem of Chesapeake Bay. We timed the X-Tags to release while striped bass were in coastal or estuarine waters prior to their annual spring spawning migration to freshwater. The release mechanism on the PSAT, which operates by electrolysis, requires > 5ppt salinity to function[1], which necessitates consideration when dealing with anadromous or catadromous fishes.

PSAT deployments in estuarine and coastal waters will likely have higher tag-to-human interaction rates than those deployed in oceanic waters, potentially leading to greater rates of tag recovery. However, to realize these potential benefits, which may be considerable in highly populated regions, the incentive (financial, material, or otherwise) for returning a recovered tag must be sufficient (Pollock et al., 2001). Historically, tag-recovery rates in PSAT studies have been very low. However, Kerstetter and Graves (2008) recently reported recoveries of 4 of 17 PSATs (23.5%) attached to sailfish released from pelagic longline operations in the Gulf of Mexico, south of Key West, FL, with all recoveries coming from the heavily used beaches of southeast Florida. Recovery of PSATs can further be aided by the use of radio antennae if tags are transmitting[1]; tags in dense cover can also be located via metal detector at close range (<0.5 m: A. Horodysky, personal obs.). Tag recovery is beneficial not only because it is possible to obtain 100% of the archived data from the PSAT, but recovered tags can be refurbished for approximately 20% of the cost of a new tag.

A second objective of this study was to assess potential differences in postrelease survival of striped bass caught on live eels rigged with J hooks and circle hooks in the winter recreational fishery. While the limited sample size precludes statistical comparisons, tags from all eight fish returned data consistent with survival. Circle hooks reduce deep-hooking, hook-induced trauma, and mortality of many fishes (Cooke and Suski, 2004; Horodysky and Graves, 2005), including striped bass (Table 1). Previous research demonstrated high mortality of striped bass deep-hooked with J hooks and additional and interactive stress-related mortality of larger striped bass caught in warm low salinity waters (> 20°C, < 10 ppt) and handled in still higher air temperatures (> 30°C) (Wilde et al., 2000; Lukacovic and Uphoff, 2002). Handling exhausted fish in warmer air can further raise basal metabolic rate, exacerbating oxygen demand and blood chemistry issues (Gingerich, et al., 2007) while simultaneously reducing respiratory gill surface area via physical collapse of the gill lamellae and adhesion of the gill filaments (Cooke et al., 2002). We observed 100% survival, including two animals deeply hooked with J hooks, caught in cool, high salinity waters (< 10°C, > 25 ppt), and handled briefly (< 2 minutes) in cool air temperatures (< 18ºC). While further work is still needed, the results of these studies suggest that the winter recreational fishery in Virginia may not be a significant source of postrelease mortality for striped bass, and that release mortality of this species likely varies temporally and spatially due to physiological stressors.

A third objective of this study was to gain insights into habitat utilization of striped bass overwintering near the mouth of Chesapeake Bay. Net displacements of the eight fish over the 30-day tagging period were limited, averaging less than 35 nmi (64.8 km). We did not use geolocation algorithms based on light and sea surface temperature data to infer horizontal movements of fish at intervals within the 30-day tagging period because the mean displacements over the 30 days were substantially less than the root mean square (RMS) errors associated with daily estimates of geolocation. Under optimal conditions such as clear pelagic seas RMS errors associated with geolocation estimates based on light and sea surface temperature data exceed 100 km (Teo et al., 2004; Nielsen and Sibert, 2007), and the hyperdynamic light conditions characteristic of turbid, tidal coastal waters such as Chesapeake Bay, which impede the accurate characterization of sunrise and sunset, would result in even greater RMS errors. Consequently, light-based geolocation would seem to have limited applicability to short term PSAT studies of estuarine and coastal fishes.

Habitat utilization studies based on PSAT data may benefit from analytical frameworks that incorporate repeated measures to account for the inherent within-individual autocorrelation (James et al., 2006; McMahon et al., 2007). Diel differences were not evident in depth or temperature utilization of coastal migrant striped bass during the January-March tag deployment period. Similarly, there were no significant differences in depth and temperature utilization among individuals or deployment days. During winter, the adult striped bass staging in coastal Virginia and North Carolina waters forage heavily on dense schools of Atlantic menhaden (*Brevoortia tyrannus*) before traveling into tributaries to spawn (Raney, 1952). The coastal waters of Virginia and North Carolina are fairly shallow and well-mixed, thus the movements of schooling striped bass during our tag deployment duration likely reflect pursuit of prey by a school of predators rather than specific selection of preferred depth or temperature ranges by individuals.

Behavioral rhythms in time-series resulting from ultrasonic telemetry and, more recently, recovered PSATs, are ideally analyzed via fast Fourier methods if all data are recovered (Hartill et al., 2003; Shepard, et al., 2006). Fast Fourier analysis of full depth time-series data streams from three recovered PSATs deployed on striped bass suggest subtle daily, 12 hour, and 8 hour periodicities. Daily periodicities may represent onshore-offshore movements of striped bass schools into shallower and deeper waters when chasing menhaden prey, 12 hour periodicities may correspond to ambient diel light regimes, and 8 hour periodicities may suggest subtle tidal or current effects in striped bass depth utilization. Mid-Atlantic coastal waters and estuaries such as Chesapeake Bay feature semidiurnal tides; tidal stage had substantial impact on movements and habitat use of striped bass in Delaware Bay (Tupper and Able, 2000). Alternately, the 8 and 12 hour periodicities observed in the striped bass data may result from the combination of harmonics resulting from behaviors not strictly sinusoidal in character (Chatfield, 1996). Fourier methods should only be applied to full (100%) data streams to avoid inferring direct spectral relationships between two adjacent data packets that are in reality separated in time by sections of untransmitted archived data.

This study investigated the applicability of a new generation of smaller PSATs for studies of estuarine and coastal fishes and provided insights into postrelease survival and habitat use of prespawn aggregating adult striped bass in the winter recreational fishery along the coast of Virginia. Results of this study suggest that tag fouling with physical structures, tag damage resulting from interaction with conspecifics, predators, or scavengers, and reduced transmission efficiency due to beaching or entanglement are not major liabilities for striped bass. In fact, the potential for reduced transmission efficiency is more than offset by increased probability of tag recovery resulting in complete data retrieval and the opportunity to reuse the tag at a greatly reduced cost. Collectively, the results of this study on striped bass suggest that the new generation of smaller PSATs may prove to be an effective tool for studying postrelease survival and habitat utilization of other estuarine and coastal fishes.

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References

Arnold, G., and H. Dewar. 2001. Electronic tags in marine fisheries research: a 30-year perspective. *In* Electronic Tagging and Tracking in Marine Fisheries Reviews: Methods and Technologies in Fish Biology and Fisheries. J.R. Sibert & J.L. Nielsen (eds) pp. 7–64. Dordrecht: Kluwer Academic Press,.

Bettoli, P. W., and R. S. Osbourne. 1998. Hooking mortality of striped bass following catch and release angling. N. Am. J. Fish. Manag. 18:609-615.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. 488 pp. Springer: NY.

Carmichael, J. T., S. L. Haeseker, and J. E. Hightower. 1998. Spawning migration of telemetered striped bass in the Roanoke River, North Carolina. Trans. Amer. Fish. Soc.127:286-297.

Chatfield, C. 1996. The analysis of time series, 6th ed. Chapman and Hall, London.

Conrath, C. L., and J. A. Musick 2008. Investigations into depth and temperature habitat utilization and overwintering grounds of juvenile sandbar sharks, *Carcharhinus plumbeus*: the importance of near shore North Carolina waters. Environ. Biol. Fish. 82:123–131.

Cooke, S. J., and C. D.Suski. 2004. Are circle hooks an effective tool for conserving marine and freshwater recreational catch-and-release fisheries? Aquatic Conserv: Mar. Freshw. Ecosyst.14: 299–326.

Cooke S. J., J. F. Schreer, D. H Wahl. and D. P. Philipp 2002. Physiological impacts of catch-and-release angling practices on largemouth bass and smallmouth bass. Am. Fish. Soc. Symp. 31:489–512.

Diodati, P. J., and R. A. Richards. 1996. Mortality of striped bass hooked and released in salt water. Trans. Am. Fish. Soc. 125:300-307.

Domeier, M. L., H. Dewar, and N. Nasby-Lucas. 2003. Mortality rate of striped marlin (*Tetrapturus audax*) caught with recreational tackle. Mar. Freshw. Res. 54(4):435−445.

Dorazio, R. M., K. A. Hattala, C. B. McColluch, and J. E. Skjeveland.

1994. Tag recovery estimates of migration of striped bass from spawning areas of the Chesapeake Bay. Trans. Am. Fish. Soc. 123:950-963.

Gingerich, A. J., S. J. Cooke, K. C. Hansonb, M. R. D., C. T. Hasler, C. D. Suski, and R. Arlinghaus.
2007. Evaluation of the interactive effects of air exposure duration and water temperature on the condition and survival of angled and released fish. Fish. Res. 86(2-3):169-178.

Graham, R. T., C. M. Roberts, and J. C. R. Smart.
2006. Diving behaviour of whale sharks in relation to a predictable food pulse. J. R. Soc. Interface. 3: 109-116.

Graves, J. E., and A. Z. Horodysky.
2008. Does hook choice matter? The effects of three circle hook models on post-release survival of white marlin. N. Am. J. Fish. Manag. 28:471-480.

Graves, J. E., B. E. Luckhurst, and E. D. Prince.
2002. An evaluation of pop-up satellite tags for estimating postrelease survival of blue marlin (*Makaira nigricans*) from a recreational fishery. Fish. Bull. 100:134−142.

Grusha, D. S.
2005. Investigation of the life history of the cownose ray, *Rhinoptera bonasus* (Mitchell 1815). MS thesis, 116pp. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA.

Grusha, D. S., and M. R. Patterson.
2005. Quantification of drag and lift imposed by pop-up satellite archival tags and estimation of the metabolic cost to cownose rays (*Rhinoptera bonasus*). Fish. Bull. 103:63–70.

Harell, R. M.
1988. Catch and release mortality of striped bass caught with artificial lures and baits. Proc. Ann. Conf. Southeast. Assoc. Fish. Wildl. Agencies. 41: 70-75.

Hartill, B. W., M. A. Morrison, M. D. Smith, J. Boubee, and D. M. Parsons.
2003. Diurnal and tidal movements of snapper (*Pagrus auratus*, Sparidae) in an estuarine environment. Mar. Freshw. Res. 54:931-940.

Horodysky, A. Z., and J. E. Graves.
2005. Application of pop-up satellite archival tag technology to estimate postrelease survival of white marlin (*Tetrapturus albidus*) caught on circle and straight-shank (“J”) hooks in the western North Atlantic recreational fishery. Fish. Bull. 103:84–96.

Horodysky, A. Z., D. W. Kerstetter, R. J. Latour, and J. E. Graves. 2007. Habitat utilization and vertical movements of white marlin (*Tetrapturus albidus*) released from commercial and recreational fishing gears in the western North Atlantic Ocean: inferences from short duration pop-up archival satellite tags. Fish. Oceanogr. 16:240-256.

Hysmith, B. T., J. H. Moczygemba, and G. R. Wilde. 1993. Hooking mortality of striped bass in Lake Texoma, Texas-Oklahoma. Proc. Ann. Conf. Southeast. Assoc. Fish. Wildl. Agencies 46:413-420.

James, M. C., C. A. Ottensmeyer, S. A. Eckert, and R. A. Myers. 2006. Changes in diel diving patterns accompanies shifts between northern foraging and southward migration in leatherback turtles. Can. J. Zool. 84:754-765.

Kerstetter, D. W., and J. E. Graves. 2008. Post-release survival of sailfish caught by commercial pelagic longline gear in the southern Gulf of Mexico. N. Am. J. Fish. Manag. 28: 1578–1586.

Kerstetter, D. W., J. J. Polovina, and J. E. Graves. 2004. Evidence of shark predation and scavenging of fishes equipped with pop-up satellite archival tags. Fish. Bull. 102:750-756.

Kirkley, J., and D. Kerstetter. 1997. Saltwater angling and its economic importance to Virginia. Univ. Virginia, Virginia Sea Gr. Pub. VSG-97-04, Charlottesville,VA, USA.,71 p.

Kohlenstein, L. C. 1981. On the proportion of the Chesapeake stock of striped bass that migrates into the coastal fishery. Trans. Am. Fish. Soc. 110:168-179.

Lukacovic, R., and J. H. Uphoff. 2002. Hook location, fish size, and season as factors influencing catch-and-release mortality of striped bass caught with bait in Chesapeake Bay. *In* Catch and release in marine recreational fisheries (J. A. Lucy and A. Studholme, eds.), p. 97-100. Am. Fish. Soc. Symp. 30, Bethesda, MD.

McGrath, P.E. 2005. Site fidelity, home range, and daily movements of white perch, *Morone americana*, and striped bass, *Morone saxatilis*, in two small tributaries of the York River,Virginia. MS thesis, 113pp.Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA.

McMahon, C. R., C. J. A. Bradshaw, and G. C. Hays. 2007. Satellite tracking reveals unusual diving characteristics for a marine reptile, the olive ridley turtle *Lepidochelys olivacea*. Mar. Ecol. Prog. Ser. 329:239-252.

Millard, M. J., S. A. Welsh, J. W. Fletcher, J. Mohler, A. Kahnle, and K. Hattala. 2003. Mortality associated with catch and release of striped bass in the Hudson River. Fish. Mgmt. Ecol. 10:295-300.

Nelson, K. L. 1998. Catch-and-release mortality of striped bass in the Roanoke River, North Carolina. N. Am. J. Fish. Manag. 18:25-30.

Nielsen, A., and J. R. Sibert. 2007. State-space model for light-based tracking of marine animals. Can. J. Fish. Aquat. Sci. 64:1055-1068

Oppenheim, A. V., and R. W. Schafer. 1989. Discrete-time signal processing. Prentice-Hall, Englewood Cliffs, NJ.

Pinheiro, J. C., and D. M. Bates. 2004. Mixed effects models in S and S-Plus (Statistics and computing). Springer-Verlag, New York.

Pollock, K. H., J. M. Hoenig, W. S. Hearn, and B. Calingaert. 2001. Tag reporting rate estimation: 1. an evaluation of the high-reward tagging method. N. Am. J. Fish. Manag. 21:521–532.

R Development Core Team 2008. R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing.

Raney, E.C. 1952. The life history of the striped bass, *Roccus saxatilis* (Walbaum). Bulletin of the Bingham Oceanographic Collection, Yale University 14: 5–97.

Richards, R. A., and P. J. Rago. 1999. A case history of effective fishery management: Chesapeake Bay striped bass. N. Am. J. Fish. Manag. 19:356-375.

Secor, D. H. 2000. Spawning in the nick of time? Effect of adult demographics on spawning behaviour and recruitment in Chesapeake Bay striped bass. ICES Journal of Marine Science 57: 403–411.

Shepard, E. L. C., M. Z. Ahmed, E. J. Southall, M. J. Witt, J. D. Metcalfe, D. W Sims. 2006. Diel and tidal rhythms in diving behavior of pelagic sharks identified by signal processing of archival tagging data. Mar. Ecol. Progr. Ser. 328:205-213.

Teo, S. L. H., A. Boustany, S. Blackwell, A. Walli, K. C. Weng, and B. A. Block

2004. Validation of geolocation estimates based on light level and sea surface temperature from electronic tags. Mar. Ecol. Prog. Ser. 283: 8198

Tupper, M., and K. W. Able. 2000. Movements and food habits of striped bass (*Morone saxatilis*) in Delaware Bay (USA) salt marshes: comparison of a restored and a reference marsh. Mar. Biol. 137:1049-1058.

Underwood, A. J. 2002. Experiments in ecology: their logical design and interpretation using analysis of variance, 504 p. Cambridge University Press. New York, NY:.

Van Winkle, W., K. D. Kumar, and D. S. Vaughan. 1988. Relative contributions of the Hudson River and Chesapeake Bay striped bass stocks to the Atlantic coastal population. *In* Science, law, and Hudson River power plants: a case study in environmental impact assessment (L. W. Barnthouse, R. J. Klauda, D. S. Vaughan, and R. L. Kendall, eds.), p. 255–266. Am. Fish. Soc., Monograph 4, Bethesda, MD.

Wilde, G. R., M. I. Muoneke, P. W. Bettoli, K. L. Nelson, and B. T. Hysmith. 2000. Bait and temperature effects on striped bass hooking mortality in freshwater. N. Am. J. Fish. Manag. 20:810-815.

Table 1. Summary of published postrelease survival experiments using J, treble and circle hooks conducted on striped bass (*Morone saxatilis*) released from the recreational fishery. Under region, F=freshwater, S=saltwater followed by the state abbreviation. Hook types are: J (straight-shank J hook), C (circle hook), and T (treble hook). For release mortality, estimates are for artificial lures (L), live bait (B), J hooks (J), or circle hooks (C).

Source	Region	Season	Hook	Bait-lure type	Release mortality
Harell (1988)	F	Winter, summer	J	Live bait, lures	L: 15.6%, B: 30.7%
Hysmith et al. (1993)	F: TX	Winter, summer	J	Live bait, lures	38%
Diodati and Richards (1996)	S: MA	Summer	J	Live bait, lures	3-26%; mean 9%
Nelson (1998)	F: NC	Spring	J, T	Live baits, lures	6-27%: mean 6.3%
Bettoli and Osborne (1998)	F: TN	Winter, summer	J , T	Live baits, lures	14-67%
Lukacovic and Uphoff (2002)	S: MD	summer	J C	Natural baits	J: 9.1% C: 0.8%
Millard et al. (2003)	F: NY	Spring	J	Natural baits	8-18%

Table 2. Hook type, hooking location, release date, fish size, PSAT data recovery, and net movement data for striped bass (*Morone saxatilis*) caught on live eels (*Anguilla rostrata*) in the winter recreational fishery off the coast of Virginia and North Carolina. Starred (*) data recovery percentages indicate instances where PSATs were physically recovered, allowing full download of all archived data. Minimum straight line displacements (MSLDs) were calculated in nautical miles (nmi) from the coordinates of tagging to the coordinates of first reliable satellite contact (Argos location code 1, 2, or 3).

Fish	Hook Type	Hooking Location	Date Released	Total length (cm)	Data recovery (%)	MSLD (nmi)
1	J	Deep	26 Jan 08	94.0	90	29.9
2	J	Upper jaw	26 Jan 08	94.0	100*	56.3
3	C	Jaw corner	26 Jan 08	96.5	87	27.8
4	C	Upper jaw	27 Jan 08	111.8	100*	34.3
5	C	Jaw corner	27 Jan 08	94.0	90	58.6
6	J	Deep	2 Feb 08	96.5	96	12.5
7	C	Upper Jaw	2 Feb 08	104.1	30	27.1
8	J	Upper Jaw	2 Feb 08	101.6	100*	32.5

Figure Legends

Figure 1. X-Tag, (Microwave Telemetry, Inc., Columbia, MD) attached to a striped bass (*Morone saxatilis*). The nylon intramuscular tag anchor was inserted approximately 5 cm towards the dorsal midline, an area where the anchor had a high likelihood of securely interlocking with the pterygiophores supporting the dorsal fin spines.

Figure 2. Depth (left axis, open black symbols) and temperature (right axis, closed grey symbols) time series from Microwave Telemetry X-Tags deployed on eight large coastal migrant striped bass (*Morone saxatilis*) from Jan-Mar 2008. Tags for fish 2, 4, and 8 were recovered and represent the full 100% downloaded datastreams.

Figure 3. Minimum straight line displacements (MSLD) in nautical miles (nmi) of eight large coastal migrant striped bass (*Morone saxatilis*) caught on recreational fishing gear and tagged with Microwave Telemetry X-Tags from Jan-Mar 2008. Arrow bases (circles) indicate location of fish tagging and release, arrow tips denote first point of contact with transmitting tag after release from the fish.

Figure 4. Time-at-depth **(A)** and time-at-temperature **(B)** histograms from Microwave Telemetry X-Tags deployed on eight large coastal migrant striped bass (*Morone saxatilis*) from Jan-Mar 2008. Each fish was given equal contribution. Error bars are ± 1 standard error.

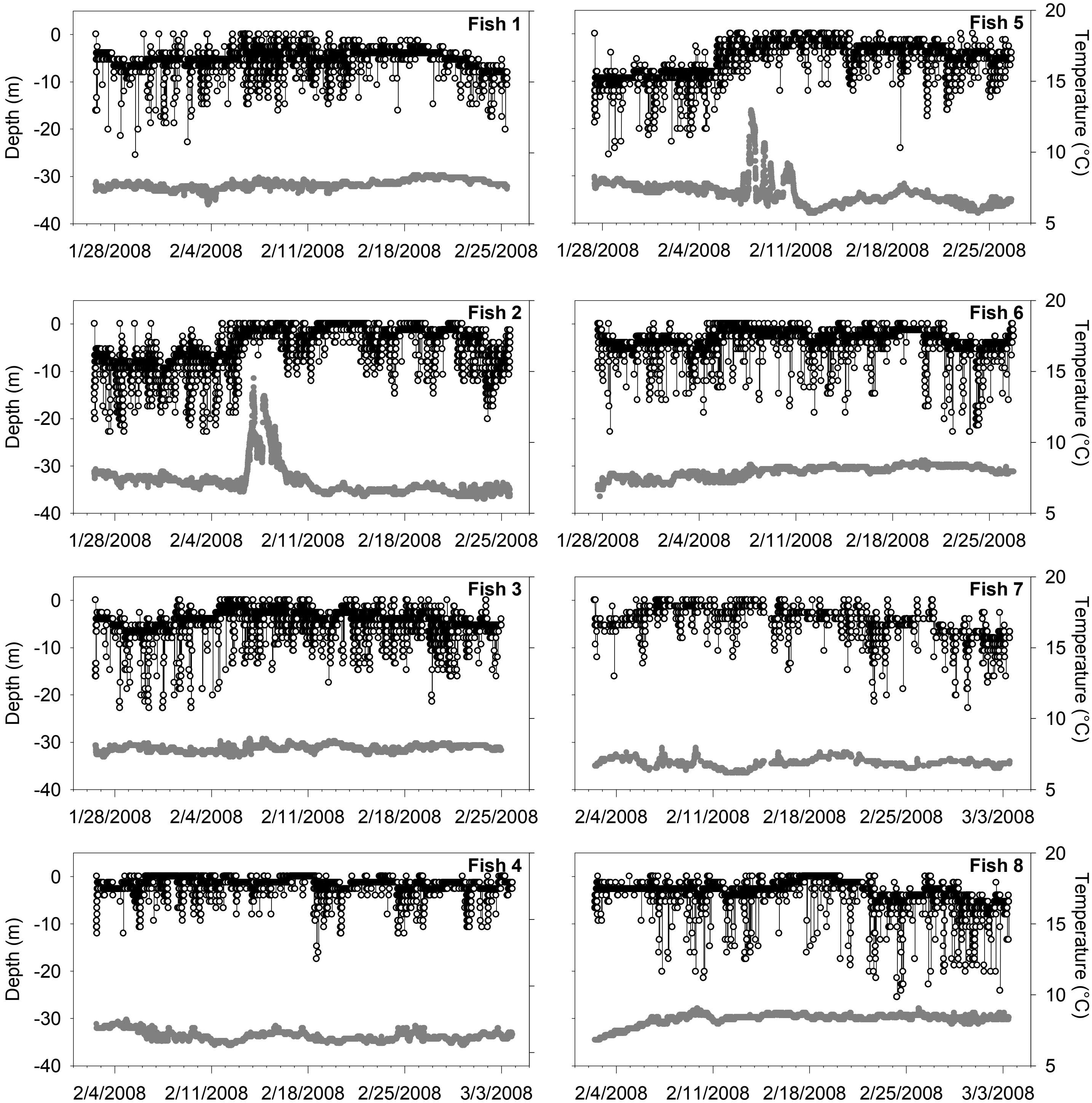
Figure 5. Fast Fourier Transform periodigrams for depth data from three recovered Microwave Telemetry X-Tags (fish 2, 4, and 8) deployed on eight large coastal migrant striped bass (*Morone saxatilis*) from Jan-Mar 2008 and physically recovered. Periods of the main spectral peaks found using the raw data and the Hamming window are identified with open circles and labeled in hours.

Figure 6. Cumulative percentage of archived data that are successfully received by the user as a function of transmitting day for a Microwave Telemetry, Inc. X-Tags High Rate Archival tags programmed with Satellite-In-View (SIV™) technology at Mid-Atlantic latitudes[2]. Due to the frequency of Argos satellite passes, tags transmitting at higher latitudes will approach asymptotic data recovery more rapidly, and those transmitting at lower latitudes will approach asymptotic data recovery more slowly.

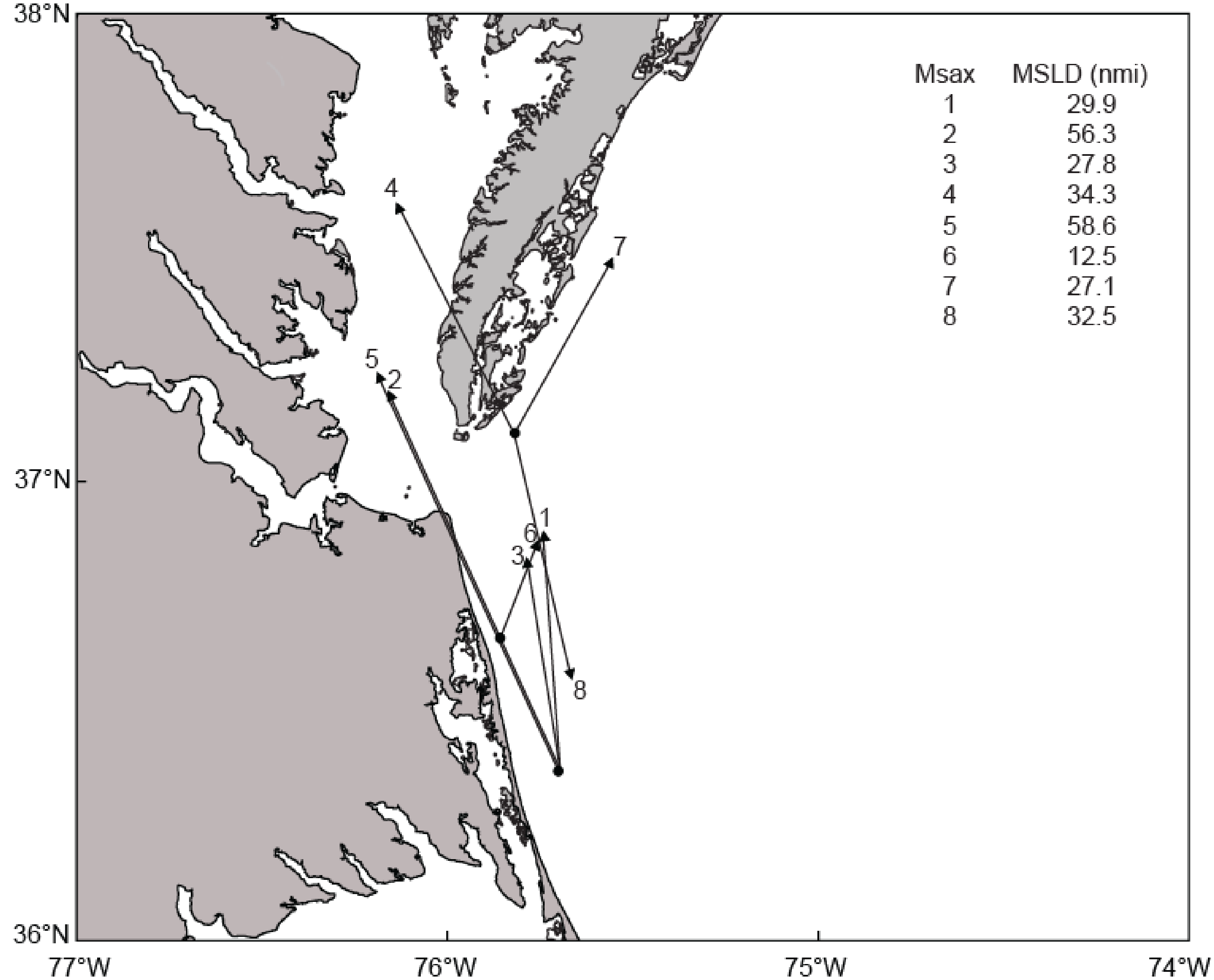
[2] R. P. Howey, 2009, University of Bath, Bath BA2 7AV, UK

Graves et al Figure 1.

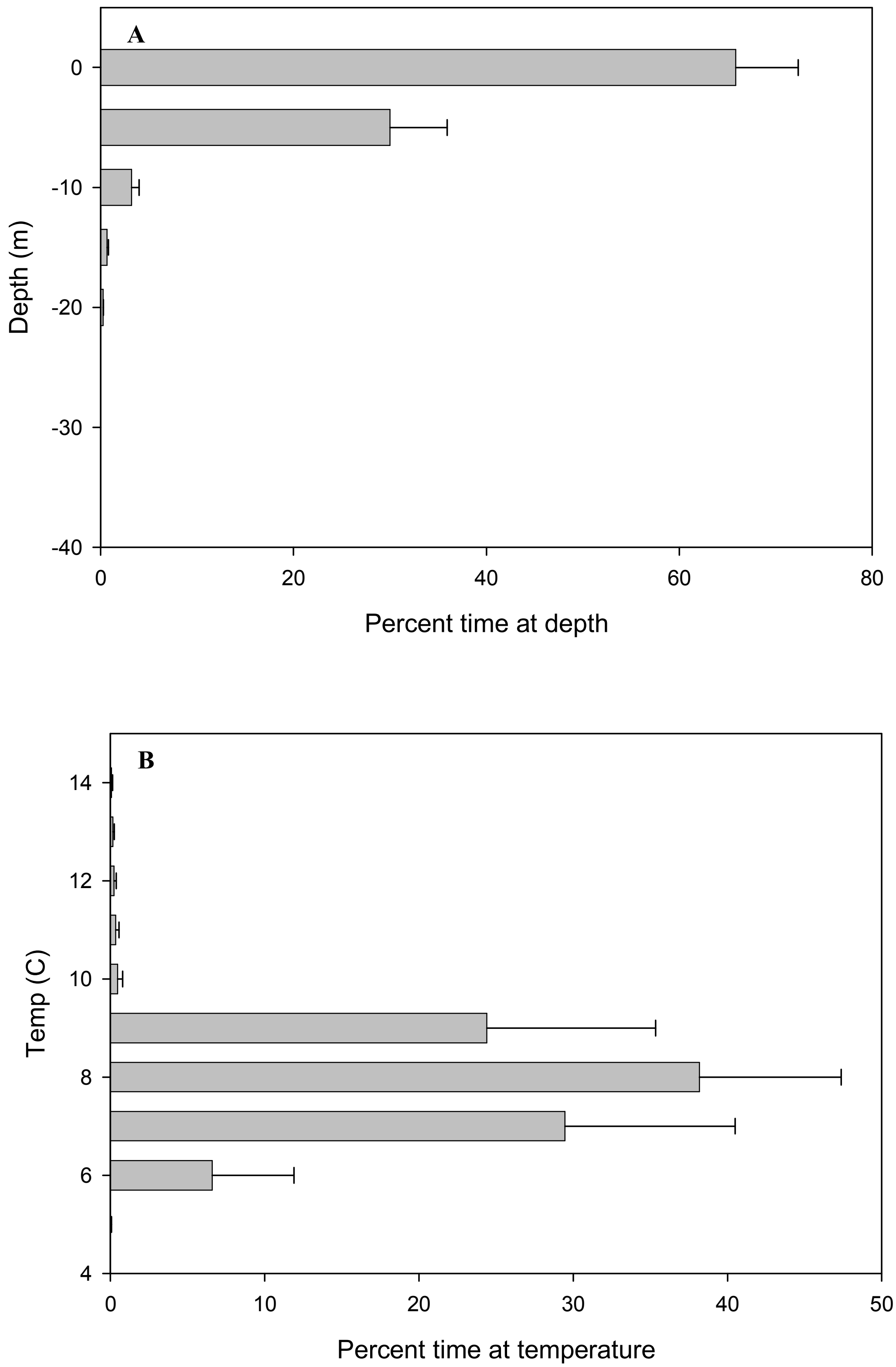
Graves et al. Figure 2



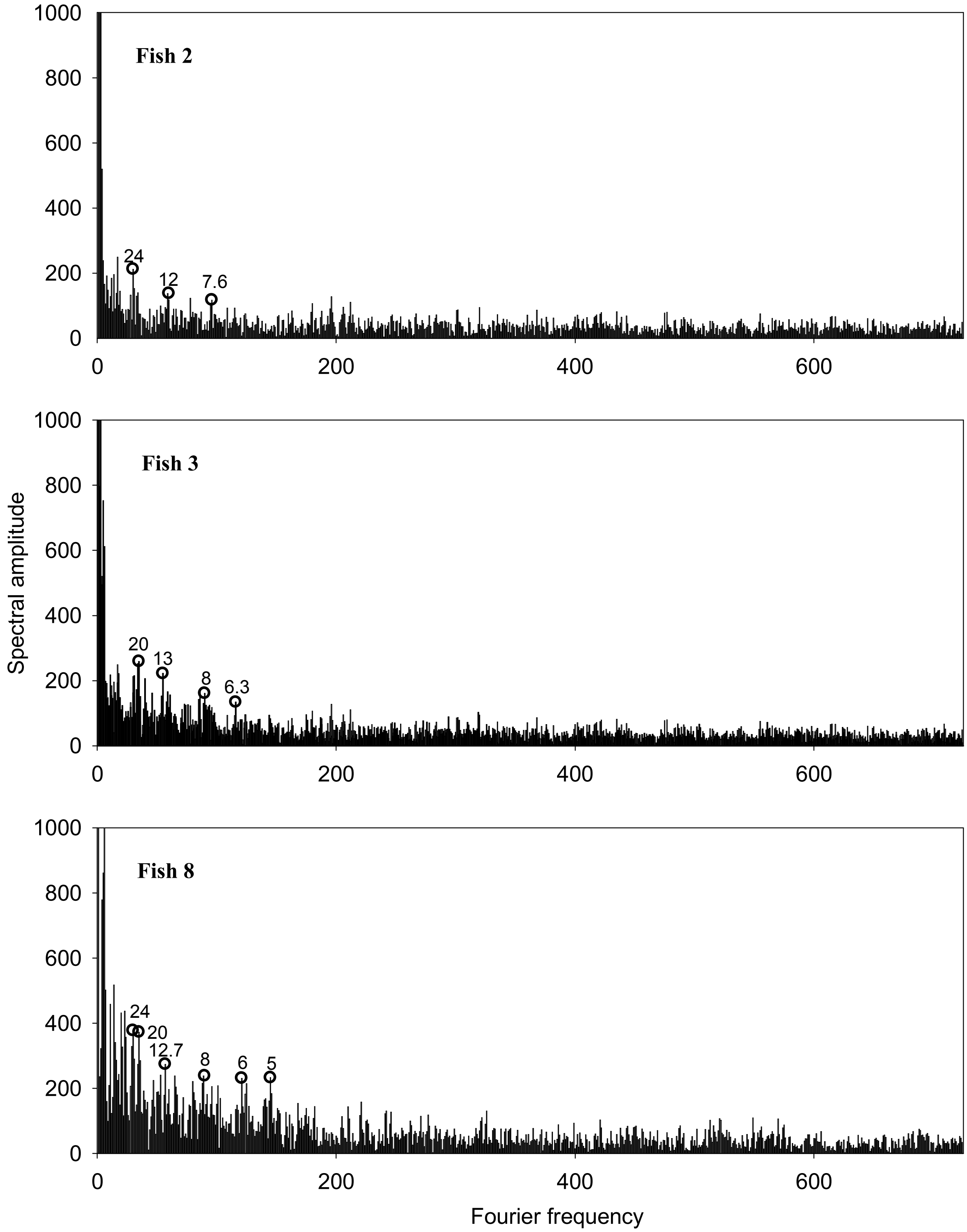
Graves et al. Figure 3



Graves et al. Figure 4



Graves et al. Figure 5



Graves et al. Figure 6