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NOTE

Short-Term Habitat Use of Juvenile Atlantic Bluefin Tuna

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Abstract

Bluefin Tuna *Thunnus thynnus* are highly sought after in commercial and recreational fisheries along the East Coast of North America. To appropriately assess and manage Atlantic Bluefin Tuna (ABT), it is necessary to understand their habitat use during multiple ontogenetic stages. We tagged 17 juvenile ABT in the northwest Atlantic Ocean with pop-up satellite archival tags (PSATs) to determine environmental factors that may affect habitat use. The PSATs were deployed off the coast of Massachusetts in August and September 2012. A generalized linear mixed model was applied to determine factors affecting the mean depth occupied by fish, and beta regression was used to understand factors affecting the proportion of time spent below the thermocline. Thermocline depth significantly affected the mean depth occupied by juvenile ABT and the proportion of time they spent below the thermocline. Time period (dawn, day, dusk, and night) also significantly affected the mean depth occupied by juvenile ABT. Additionally, the time period × lunar illumination interaction had a significant effect on the proportion of time spent below the thermocline. This study is the first to demonstrate that environmental factors such as thermocline depth, time period, and lunar illumination can significantly impact vertical habitat use by juvenile ABT and demonstrates the utility of generalized linear mixed models for investigating fish habitat use.

Bluefin Tuna *Thunnus thynnus* support commercial and recreational fisheries along the East Coast of North America. The commercial fishery in the Atlantic Ocean targets large adult Bluefin Tuna, whereas the recreational fishery is supported by smaller fish, which are often immature (ICCAT 2014). An understanding of habitat use by Atlantic Bluefin Tuna (ABT) at multiple ontogenetic stages is essential for accurately assessing their abundance and for determining appropriate management strategies.

Although habitat use by adult ABT is well studied (Lutcavage et al 2000; Block et al. 2001; Newlands et al. 2004; Schick et al. 2004; Stokesbury et al. 2004; Wilson et al. 2005; Teo et al. 2007; Walli et al. 2009; Druon et al. 2016), less information is available regarding habitat use by juvenile ABT (Brill et al. 2002; Galuardi and Lutcavage 2012; Druon et al. 2016). Additionally, studies of juvenile ABT habitat use have focused on temporal changes in habitat use at diel and seasonal levels (Brill et al. 2002; Galuardi and Lutcavage 2012; Druon et al. 2016) and on how horizontal habitat use changes with factors like sea surface temperature and chlorophyll concentration (Druon et al. 2016); however, the manner in which environmental factors may affect vertical habitat use by juvenile ABT has not been investigated.

During summer, juvenile ABT spend the majority (>90%) of their time in the upper 30 m of the water column (Brill et al. 2002); the mean depth occupied is shallower in summer (5–12 m) than in winter (41–58 m; Galuardi and Lutcavage 2012). Juvenile fish may use deep waters as well: pop-up satellite archival tags (PSATs) have recorded individuals making vertical excursions to depths up to 800 m (Galuardi and Lutcavage 2012). Due to their extensive vertical movements, juvenile ABT may encounter a wide range of temperatures in a relatively short time interval. Although juvenile ABT are known to spend the majority of their time in waters warmer than 17°C during

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summer, they also use waters of 10°C or less for short periods (Brill et al. 2002; Galuardi and Lutcavage 2012; Druon 2016). Juvenile ABT may exploit these deeper, cooler waters in order to feed—similar to the observed habitat use of Pacific Bluefin Tuna *Thunnus orientalis*, Skipjack Tuna *Katsuwonus pelamis*, and Yellowfin Tuna *T. albacares* (Marchal and Lebourges 1996; Kitagawa et al. 2007b)—or to behaviorally thermoregulate, as seen in Yellowfin Tuna (Block et al. 1997). Although both juvenile and adult ABT have been documented as making excursions below the thermocline (Stokesbury et al. 2004; Galuardi and Lutcavage 2012), the thermocline may act as a barrier to movement for adult ABT (Wilson et al. 2005; Walli et al. 2009). However, the potential for the thermocline to act as a barrier has not been investigated for juvenile ABT.

Other factors, such as time of day and lunar illumination, are known to affect habitat use by adult ABT (Wilson et al. 2005), Bigeye Tuna *T. obesus* (Lam et al. 2014), Albacore *T. alalunga* (Cosgrove et al. 2014), and juvenile Southern Bluefin Tuna *T. maccoyii* (Bestley et al. 2009) and may affect habitat use by juvenile ABT as well. For Albacore, the percentage of time spent in shallow waters (<50 m) was typically greater at night (86%) than during the day (62%; Cosgrove et al. 2014). Adult ABT also were reported to exhibit diel variation in habitat use, maintaining a greater mean depth during the day than during dawn, dusk, or night (Wilson et al. 2005). No statistical differences in diel habitat use have been observed for juvenile ABT (Brill et al. 2002; Galuardi and Lutcavage 2012). Increasing lunar illumination (from new moon to full moon) was associated with increasing mean depth occupied by adult ABT (Wilson et al. 2005) and was significantly correlated with mean nighttime depth for adult Bigeye Tuna (Lam et al. 2014) and juvenile Pacific Bluefin Tuna (Kitagawa et al. 2007a). For juvenile Southern Bluefin Tuna, lunar phase was also an important factor in models predicting mean depth, maximum depth, proportion of time at the surface, and proportion of time at depths exceeding 100 m (Bestley et al. 2009). This relationship has not yet been examined for juvenile ABT.

As with other large pelagic predators, habitat use by juvenile ABT is likely regulated by their physiology (Brill 1994; Brill et al. 2005; Galli et al. 2009; Block et al. 2011), although other factors (e.g., prey availability) may also affect habitat use (Bertrand et al. 2002; Schick and Lutcavage 2009). To investigate how environmental factors influence short-term habitat use by juvenile ABT, we used PSATs to gather high-frequency environmental data from individual fish (Horodysky et al. 2007; Graves et al. 2009). We examined the following null hypotheses: (1) environmental factors do not affect the mean depth occupied by juvenile ABT and (2) environmental factors do not affect the proportion of time juvenile ABT spend in waters below the thermocline.

METHODS

The experimental protocols used in the present study were approved by the Institutional Animal Care and Use Committee (IACUC-2011-07-11-7390-jegrav) at the College of William and Mary and complied with all applicable U.S. guidelines.

Tag deployment.—Juvenile ABT (91–119 cm curved fork length) were captured from coastal waters of Massachusetts (n = 17) between August 2 and September 22, 2012 (Figure 1), reflecting the availability of fish to the recreational fishery during summer 2012. Juvenile ABT were captured via methods commonly employed in the U.S. recreational fishery (i.e., rod and reel, with a lure or lure–bait combination rigged with a large "J" hook [8/0–10/0] as the terminal tackle). A minimum of 30 min elapsed between tagging events to reduce the likelihood of sampling multiple individuals from a single school. Fish were brought onto the vessel, measured for curved fork length, and tagged with a PSAT (High-Rate X-Tag; Microwave Telemetry, Columbia, Maryland). The tag anchor was inserted into the dorsal musculature at a point directly posterior and ventral to the anterior insertion of the first dorsal fin; the fish was then released. The entire tagging process was brief (~1.5 min on average). The tag anchor (3.2 cm long × 2.4 cm wide) was a hydroscopic surgical-grade nylon assembly that was attached to the PSAT with a tether consisting of 16 cm of monofilament fishing line (91-kg breaking strength). A more detailed description of the PSAT assembly and deployment protocol is given by Marcek and Graves (2014).

The PSATs were programmed to record pressure (depth), temperature, and light every 5 min and to release after a 31-d deployment. After release, the PSATs floated to the surface and transmitted their archived data to the Advanced Research and Global Observation Satellite system. To ensure that tags would be released from moribund fish, the PSATs were programmed with two emergency release mechanisms as described by Musyl et al. (2011). The PSAT was released from a moribund fish if a constant depth was recorded for 4 d or if a maximum depth of 1,250 m was reached.

Analyses.—We used the data from each PSAT to (1) model the mean depth occupied by juvenile ABT and the proportion of time they spent below the thermocline and (2) explore the effects

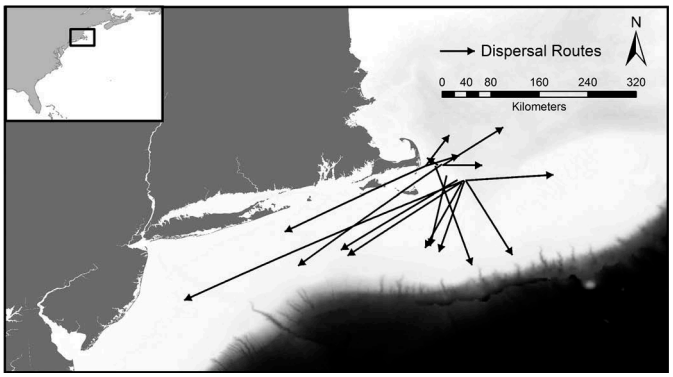


FIGURE 1. Map of the tag deployment location and dispersal routes for the 16 juvenile Atlantic Bluefin Tuna (91–119 cm curved fork length) with reporting pop-up satellite archival tags deployed in August and September 2012 off the Massachusetts coast. Fish were captured using standard trolling methods. Arrows indicate dispersal direction and distance.

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of environmental factors on habitat use by juvenile ABT. The mean depth (m) was calculated for dawn, day, dusk, and night periods, whereas the proportion of time spent below the thermocline was calculated for day and night only (as defined below). The proportion of time spent below the thermocline was calculated as the time (min) during which the fish used waters below the thermocline divided by the total time (min) in the period of interest. If there was no discernible thermocline, the corresponding data were excluded from the analysis. The predictors included in the models of mean depth and proportion of time spent below the thermocline were time period (dawn, day, dusk, or night), lunar illumination, and thermocline depth.

For the mean depth model, we defined four discrete 1-h time periods (dawn, day, dusk, and night) from each 24-h day to investigate the effects of diel and crepuscular periods on juvenile ABT habitat use. Times of sunrise and sunset from the U.S. Naval Observatory Web site (aa.usno.navy.mil/faq/docs/RST_defs.php) were used to define these periods. Crepuscular periods were defined as sunrise and sunset ±30 min, day was defined as the midpoint between sunrise and sunset ±30 min, and night was defined as the midpoint between sunset and sunrise ±30 min. One-hour intervals were used for each time period to reduce the likelihood of dampening crepuscular signals by the inclusion of observations from adjacent times and to reduce correlations among observations within a day. For the model examining the proportion of time spent below the thermocline, we defined two 6-h periods (day and night): day was defined as the midpoint between sunrise and sunset ±3 h, and night was defined as the midpoint between sunset and sunrise ±3 h. The 6-h time intervals were used to ensure that the number of observations was sufficient for calculating the proportion of time spent below the thermocline. In addition, lunar illumination data were acquired from the U.S. Naval Observatory Web site. Lunar illumination was reported as the proportion of the moon that was illuminated (0.0–1.0), where 0.0 represents the new moon and 1.0 represents the full moon.

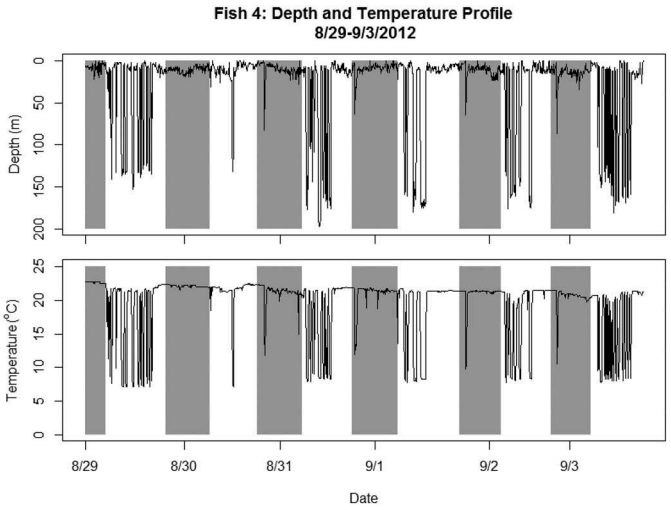


FIGURE 2. Depth and temperature profiles over 6 d in late August and early September 2012 for a juvenile Atlantic Bluefin Tuna (fish 4) that was tagged with a pop-up satellite archival tag and released off the Massachusetts coast. This individual displayed typical behavior, remaining in warmer waters near the surface for the majority of tag deployment but making periodic excursions to cooler, deeper waters. The majority of vertical excursions also occurred during the day, whereas the fish remained near the surface at night (gray-shaded bars).

We used vertical profiles of depth and temperature from tagged ABT to calculate thermocline depth (Figure 2). Depth–temperature profiles were created for each fish by aggregating data into 5-d intervals, binning the depth data into 1-m intervals, and calculating the mean temperature for each bin (±SE;

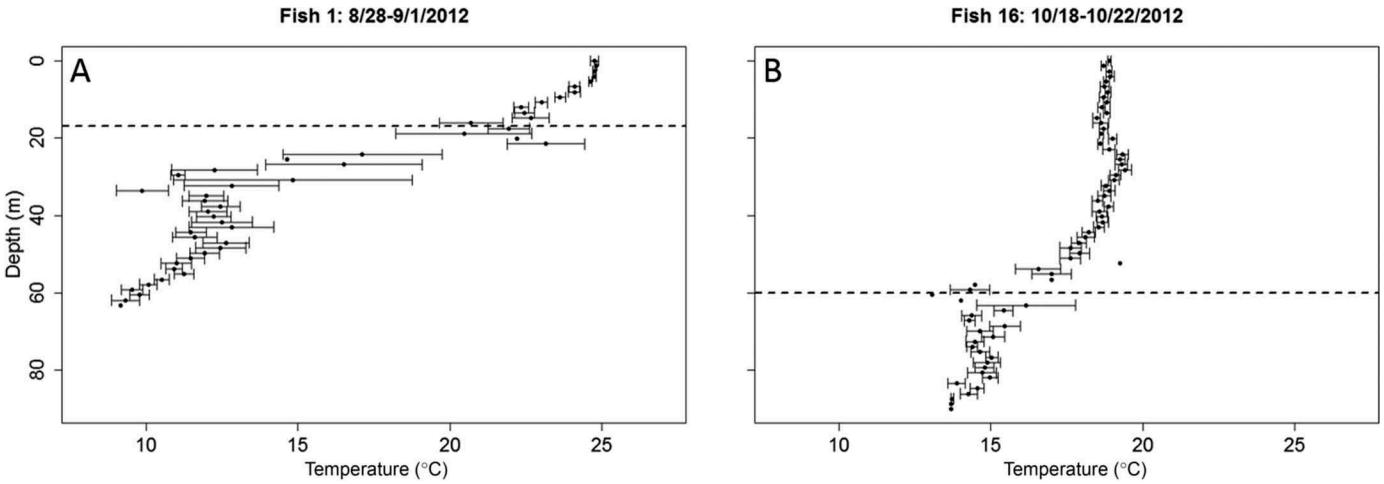


FIGURE 3. Vertical profiles of the water column occupied by juvenile Atlantic Bluefin Tuna (with pop-up satellite archival tags) from August to October 2012 offshore of Massachusetts. Examples of depth–temperature profiles for two individuals at different times during the tag deployment are shown: **(A)** fish 1 during late August and **(B)** fish 16 during mid-October. The thermocline (horizontal dotted line) was established at 15 m in August (A) and increased to 60 m in mid-October (B). The mean temperature estimate for each depth is presented with ±SE.

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Figure 3). Data were aggregated over 5-d intervals to ensure that there were sufficient observations to construct depth–temperature profiles, thus allowing us to reconstruct the physical conditions of the water column in areas occupied by the fish. The depth of the thermocline was identified as the depth with the maximum gradient in water temperature. Days for which the thermocline could not be defined were omitted from this analysis.

Mean depth occupied by juvenile Atlantic Bluefin Tuna.—The mean depth occupied by juvenile ABT was analyzed by using a generalized linear mixed model with repeated measures (MIXED procedure in the Statistical Analysis System [SAS] version 9.3; SAS Institute, Cary, North Carolina). Mean depth was $\log_e$ transformed to meet the assumption of homogeneity of variance (Logan 2010). To allow for this transformation, 0.01 m was added to the zero observations (mean depth = 0 m when a fish was at the surface during the entire 1-h period of observation); zero observations constituted 3 (0.002%) of the 1,812 observations. Because multiple observations of depth and temperature were collected for each fish, we assumed that consecutive observations from the same fish were correlated. Therefore, we used a mixed model with repeated measures to model the mean depth occupied by juvenile ABT, with individual fish as the subject. Because individual ABT in this study represented a random sample from the population and because substantial variation in habitat use was observed among fish, we treated individual fish as a random factor; all other factors (thermocline depth, time period, and lunar illumination) were considered fixed effects. Additionally, *t*-tests were used to evaluate the significance of the factors' effects. We considered four covariance structures to describe the correlation between responses of an individual fish: variance components, compound symmetry, first-order autoregressive, and banded Toeplitz (Littell et al. 2000). Akaike's information criterion (AIC) was used to compare models that differed in covariance structure, and the best model was selected based on the lowest AIC value (Logan 2010). The covariance structure that best fit the data (eight-banded Toeplitz) was used in the final model. In addition, plots revealed potential two-way interactions (1) between thermocline depth and lunar illumination and (2) between time period and lunar illumination. Models that contained interactions were evaluated to determine whether the AIC value was lower (i.e., better performance) than that of the simpler model lacking the interactions (Hastie et al. 2009); we found that mean depth models lacking the interaction terms exhibited a better fit to the data, and therefore the interaction terms were omitted. The final model used in our analysis for mean occupied depth followed the form

$$Y_{ij} = \mu + \rho_i + \alpha + \gamma + \varepsilon_{ij}, \quad (1)$$

where Y_{ij} is the mean depth occupied by individual j in time period i; μ is the overall average mean depth occupied; α is the effect of thermocline depth; ρ is the effect of period (dawn, day, dusk, or night); γ is the effect of lunar illumination; and ε_{ij} is the random unexplained error.

Proportion of time spent below the thermocline.—The proportion of time that juvenile ABT were below the thermocline during the day or night period was bounded within the interval [0, 1]; furthermore, like most proportion data, the response data were characterized by skewness. These two properties violate the assumptions of normality and homogeneity of variance, which are required for the use of general linear models (Swearingen et al. 2012). We therefore used the beta distribution to model the response in a regression framework (Swearingen et al. 2012). As before, we considered and modeled the correlations between repeated observations from the same fish.

The proportion of time spent below the thermocline was analyzed using a beta regression approach with repeated measures as implemented with the GLIMMIX (generalized linear mixed models) procedure in SAS. A generalized estimating equation (GEE) approach was used to estimate model parameters due to the correlations among repeated observations. Because the GEE in GLIMMIX uses a pseudolikelihood estimation technique, model fit could not be assessed with the typical criteria (AIC, Bayesian information criterion, etc.; Vonesh 2012). Instead, we evaluated the adequacy of the modeled covariance structure by using the variance of the Pearson residuals (Dickey 2010) and the ratio of the generalized chi-square statistic (χ^2) to its degrees of freedom (df; Schabenberger 2005). If the variance of the Pearson residuals was near 1.00, the covariance structure was considered an adequate fit to the data (Dickey 2010). Additionally, a χ^2:df ratio close to 1.00 indicates that the variability in the data was appropriately modeled and that there is no residual overdispersion (Schabenberger 2005). We investigated models that used either a variance components function or a first-order autoregressive function to describe the covariance structure; based on the variance of the Pearson residuals and the χ^2:df ratio, we determined that the first-order autoregressive structure resulted in a better model fit. Because it was unlikely that repeated observations from each fish were completely independent of one another, the variance components structure—which assumes zero correlation—was deemed unreasonable for these data. Potential interactions (thermocline depth × lunar illumination; time period × lunar illumination) were considered. Based on inspection of the interaction plots, the time period × lunar illumination interaction was included in the final model, which followed the form

$$Y_{ij} = \mu + \rho_i + \alpha + \gamma + (\rho_i \times \gamma) + \varepsilon_{ij}, \quad (2)$$

where Y_{ij} is the transformed proportion of time spent below the thermocline by individual j during time period i; μ is the

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overall mean proportion of time spent below the thermocline; and model predictors are as defined for equation (1) except that the period effect ρ includes only day and night. As before, individual fish were included as a random factor.

RESULTS

Sixteen (94%) of the 17 PSATs reported between 80% and 100% of their archived data (mean ± SE = 88.3 ± 1.3%); one tag did not report (Table 1). Of the 16 reporting tags, one released prematurely at 6 d postdeployment. Additionally, one PSAT (and presumably the fish carrying it) was inferred to have been consumed by a predator 12 d after deployment (see Marcek and Graves 2014 for details). For that individual, the depth, temperature, and light profiles were consistent with normal behavior of juvenile ABT up to day 12 postdeployment; therefore, we considered data from only the first 11 d after tag deployment. Pooling across individuals, we observed that juvenile ABT occupied the upper 30 m of the water column for 81.1 ± 3.3% (mean ± SE) of their time, and waters between 17°C and 24°C were used 84.0 ± 3.3% of the time. Additionally, the pop-up locations of tags indicated a variety of dispersal patterns away from the tagging locations, with several fish moving in a generally southward direction toward winter foraging grounds (Figure 1). Minimum straight-line displacements ranged from 18 to 402 km (Table 1).

TABLE 1. Tag deployment date, curved fork length (CFL) of tagged fish, number of days the tags were deployed, the percentage of archived data recovered from each tag, and the minimum straight-line distance traveled by each juvenile Atlantic Bluefin Tuna (n = 17) tagged with pop-up satellite archival tags offshore of Chatham, Massachusetts, during 2012.

Fish	Date of tag deployment	CFL (cm)	Days deployed	% of data recovered	Minimum straight-line distance (km)
1	Aug 2	109	31	89	207.3
2	Aug 2	107	31	85	44.4
3	Aug 2	107	6	100	59.4
4	Aug 4	107	31	80	97.9
5	Aug 29	117	31	89	118.0
6	Sep 12	114	31	86	134.6
7	Sep 12	114	31	86	109.6
8	Sep 14	109	31	88	48.6
9	Sep 14	117	31	87	245.1
10	Sep 15	117	31	87	402.5
11	Sep 15	114	31	88	189.9
12	Sep 15	91	31	91	121.3
13	Sep 21	91	16	98	18.0
14	Sep 21	119	31	89	169.8
15	Sep 22	99	31	90	116.4
16	Sep 22	99	31	80	185.8
17	Sep 22	119		Did not report	

TABLE 2. Parameter estimates for the model describing the mean depth occupied by juvenile Atlantic Bluefin Tuna.

Factor	Estimate	t	P
Intercept	1.56	6.62	<0.01
Time period			
Dawn	0.21	2.05	0.04
Day	0.31	2.98	<0.01
Dusk	0.13	1.25	0.21
Night	0	–	–
Lunar illumination	0.19	1.88	0.06
Thermocline depth	0.04	5.35	<0.01

Mean Depth Occupied by Juvenile Atlantic Bluefin Tuna

Variation among individual fish explained 15.4% of the overall variation in mean depth occupied by juvenile ABT. Inclusion of individual fish as a random factor resulted in a lower AIC score, indicating that differences in the behavior of individuals explained a significant portion of the variability in mean occupied depth. Fish occupied a significantly greater mean depth during dawn (ρ_{dawn} = 0.21, t = 2.05, P = 0.04) and day (ρ_{day} = 0.31, t = 2.98, P < 0.01) than at night (Table 2; Figure 4). The mean depth occupied by juvenile ABT also increased significantly with thermocline depth (α = 0.03, t = 5.35, P < 0.01). Although lunar illumination was not a significant factor in the model, the data

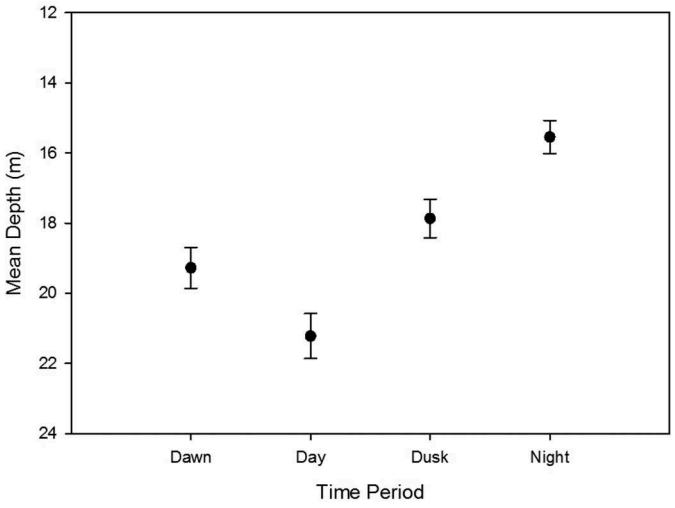


FIGURE 4. Mean depth occupied by juvenile Atlantic Bluefin Tuna (n = 16) during four time periods: dawn, day, dusk, and night. Each point represents the model-predicted mean depth (±SE) occupied during a given time period. Fish were tagged with pop-up satellite archival tags and released offshore of Massachusetts in August and September 2012.

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TABLE 3. Parameter estimates for the model describing the proportion of time spent below the thermocline by juvenile Atlantic Bluefin Tuna.

Factor	Estimate	t	P
Intercept	–2.13	–2.91	<0.01
Thermocline depth	–0.04	–2.09	0.05
Time period × lunar illumination			
Day	0		
Night	2.02	2.81	<0.01

suggested that the mean occupied depth increased with increasing lunar illumination ($\gamma = 0.19$, $t = 1.88$, $P = 0.06$).

Proportion of Time Spent below the Thermocline

The proportion of time in which juvenile ABT used waters below the thermocline was significantly affected by thermocline depth. As thermocline depth increased, the proportion of time spent below the thermocline decreased ($\alpha = –0.04$, $t = –2.09$, $P = 0.05$; Table 3). Additionally, the time period × lunar illumination interaction significantly affected the proportion of time spent below the thermocline. Regardless of lunar illumination, the proportion of time juvenile ABT spent below the thermocline was greater during the day than at night (Figure 5). Additionally, there was little effect of lunar illumination on the proportion of time spent below the thermocline during the day, but as lunar illumination increased, the proportion of time spent below the thermocline at night increased relative to the proportion spent there during the day ($\rho_{night} \times \gamma = 2.02$, $t = –2.81$, $P < 0.01$; Figure 5).

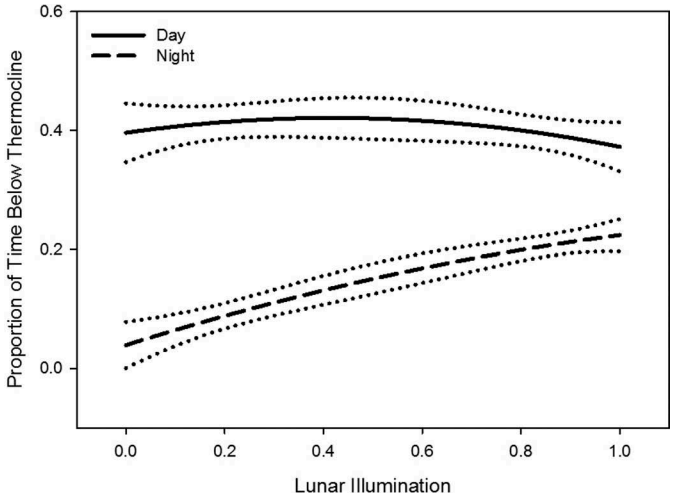


FIGURE 5. Proportion of time for which juvenile Atlantic Bluefin Tuna (ABT; $n = 16$) occupied waters below the thermocline in relation to increasing lunar illumination. The fish were tagged with pop-up satellite archival tags and released offshore of Massachusetts in August and September 2012. Day is represented with a solid line, and night is represented with a dashed line. The curves presented here are fitted to predictions from the model describing the proportion of time spent below the thermocline. Dotted lines represent the 95% confidence interval surrounding the model-predicted mean response.

DISCUSSION

The observation that juvenile ABT occupy greater mean depths during dawn and day than at night has not been noted in previous studies of juvenile ABT habitat use (Brill et al. 2002; Galuardi and Lutcavage 2012). This behavior may be related to the feeding ecology of ABT. The retinal cell density in the eyes of tunas indicates that their best visual axis is above and in front of the fish's direction of travel (Tamura and Wilsby 1963; Kawamura et al. 1981; Somiya et al. 2000), thus allowing ABT to detect the silhouettes of prey against downwelling light. As the sun rises, this strategy may provide a means of locating prey that have moved closer to the surface at night, thereby increasing foraging efficiency of juvenile ABT. They may employ a similar strategy during the day by using downwelling sunlight to detect silhouetted prey swimming higher in the water column.

The time period × lunar illumination interaction had a significant effect on the proportion of time spent below the thermocline by juvenile ABT. As lunar illumination increased, the proportion of time spent below the thermocline increased at night relative to day. Juvenile ABT likely spend more time below the thermocline during periods of greater lunar illumination so as to detect the silhouettes of prey and to increase their feeding efficiency as described above. Our results suggested that the mean depth occupied by juvenile ABT also increased with increasing lunar illumination, although the effect was not significant. Further investigation of this relationship is necessary, as lunar illumination has been shown to impact habitat use by other tunas, such as the Bigeye Tuna (Lam et al. 2014) and Southern Bluefin Tuna (Bestley et al. 2009).

We demonstrated that thermocline depth was a significant factor determining both the mean depth occupied by juvenile ABT and the proportion of time they spent below the thermocline. Depth–temperature profiles from the PSATs indicated that the thermocline in waters offshore of Massachusetts between late August and early September 2012 was approximately 15 m. Thermocline depth increased to about 60 m by late October, coincident with increases in the mean depth occupied by juvenile ABT and decreases in the proportion of time spent below the thermocline. Similar to the ABT observed by Brill et al. (2002) and Galuardi and Lutcavage (2012), the fish in this study made periodic excursions to depth but spent the vast majority of their time above the thermocline. Such behavior is also similar to that of juvenile Pacific Bluefin Tuna, which are primarily found above the thermocline but make periodic excursions to depth (Kitagawa et al. 2007a). Although juvenile ABT may exploit waters below the thermocline for feeding and behavioral thermoregulation, the amount of time juvenile

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ABT can exploit these deep, cool waters is likely limited by their physiology. Altantic Bluefin Tuna are known to exhibit regional endothermy, maintaining their red muscle tissue and viscera above ambient temperature (Carey and Lawson 1973); however, the heart is not maintained above ambient temperature. Therefore, the cardiac function of ABT may limit the amount of time they can spend in cold water. Cardiac data are not available for ABT, but the heart rate of juvenile Pacific Bluefin Tuna was shown to decrease with decreasing temperature (Clark et al. 2013), indicating impaired cardiac function at low temperatures.

The relationships between thermocline depth and the mean depth occupied by juvenile ABT and the proportion of time spent below the thermocline may reflect a strategy for optimizing the fish's foraging efficiency while allowing them to remain within their physiological tolerance. As thermocline depth increases, juvenile ABT may be able to occupy deeper waters for a longer period of time because they are not moving through the thermocline but instead remain in the relatively warm, well-mixed layer of the water column, which allows them to forage more efficiently.

Habitat use by potential prey is likely to change with environmental factors (e.g., thermocline depth and lunar illumination), and juvenile ABT likely react to changes in prey depth. Incidental observations of stomach contents from juvenile ABT indicated that some fish had recently fed on sand lances *Ammodytes* spp., while others fed primarily on Atlantic Herring *Clupea harengus* (B. J. Marcek, personal observation). Juvenile ABT may alter their habitat use to maximize their co-occurrence with prey species such as sand lances and Atlantic Herring (Eggleston and Bochenek 1990; Chase 2002; Schick and Lutcavage 2009; Logan et al. 2011, 2015); such behaviors have been observed in other large pelagic fishes like the Bigeye Tuna, Yellowfin Tuna (Grubbs and Holland 2003), and Swordfish *Xiphias gladius* (Carey 1990). Atlantic Herring, which are commonly found from Cape Cod to Greenland (Bigelow and Schroeder 2002), occupy depths of 0 to 200 m (Whitehead 1985) and prefer temperatures between 8°C and 12°C (Stickney 1969). Sand lances are widely distributed from inshore waters to offshore banks (Bigelow and Schroeder 2002) from Cape Hatteras to Greenland (Nizinski et al. 1990) and are abundant from New Jersey to the Gulf of Maine (Bigelow and Schroeder 2002). Sand lances are most commonly found at temperatures ranging from –2°C to 11°C (Scott 1968) and move inshore during summer, particularly at northern latitudes (Reay 1970). Differences in the distributions of sand lances and Atlantic Herring and their co-occurrence with juvenile ABT may cause those prey fishes to have differential predation susceptibility. Sand lances and Atlantic Herring are often found at temperatures that occur below the thermocline during summer; this may induce more frequent vertical feeding excursions by juvenile ABT, potentially leading to increased mean occupied depths and more time spent below the thermocline.

Most of our study fish displayed vertical movement patterns similar to those described in previous studies of juvenile ABT (Brill et al. 2002; Galuardi and Lutcavage 2012): they spent the majority of their time in warm, shallow waters while making periodic excursions to depths well below the thermocline. Additionally, most of the fish in this study displayed diel differences in habitat use, as their vertical excursions took place primarily during daylight.

Our results show that environmental factors, such as thermocline depth, lunar illumination, and time period, can have significant effects on habitat use by juvenile ABT. However, because of the small sample size included in these analyses (n = 16) and the small spatial and temporal scales covered, additional data will help to elucidate some of the spatial and temporal dynamics of ABT habitat use that were beyond the scope of this project. Furthermore, a temporally intensive assessment of pelagic prey distribution and abundance, conducted simultaneously with a tagging study of juvenile ABT, would allow investigation of prey abundance effects on juvenile ABT habitat use. A better understanding of how the distribution of juvenile ABT is affected by environmental factors and prey abundance will improve spatial and temporal estimates of catchability in the recreational fishery and will result in more accurate estimates of juvenile ABT abundance.

Finally, we note that the beta regression technique allowed the use of proportion data to describe habitat utilization—something that was not possible with conventional linear modeling techniques without transforming the data to values outside the bounded range of [0, 1]. Beta regression could be incorporated into many habitat use studies in addition to studies that employ PSATs. For instance, implantable archival tags could yield similar data and could allow investigation of seasonal components. Beta regression models could also be applied to data from studies using passive acoustic arrays to monitor the use of a prescribed habitat or a marine protected area. Despite the fact that beta regression is new to fisheries research, it clearly can be a useful tool for analyzing habitat use from temporally intensive data.

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