

Using bone measurements to estimate the original sizes of bluefish (*Pomatomus saltatrix*) from digested remains

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The ability to estimate the original size of an ingested prey item is an important step in understanding the community and population structure of piscivorous predators (Scharf et al., 1998). More specifically, knowledge of original prey size is essential for deriving important biological information, such as predator consumption rates, biomass of the prey consumed, and selectivity of a predator towards a specific size class of prey (Hansel et al., 1988; Scharf et al., 1997; Radke et al., 2000). To accurately assess the overall “top-down” pressure a predator may exert on prey community structure, prey size is crucial. However, such information is often difficult to collect in the field (Trippel and Beamish, 1987). Stomach-content analyses are the most common methods for examining the diets of piscivorous fish, but the prey items found are often thoroughly digested and sometimes unidentifiable. As a result, obtaining a direct measurement of prey items is frequently impossible.

Because of the problems of reconstructing original prey size directly from prey remains, numerous methods involving correlations between measurements of specific morphological features of the prey and prey size (length) have been devised. External body measures such as eye diameter, and caudal peduncle depth (Crane et al., 1987; Serafy et al., 1996; Scharf et al., 1997), as well as numerous internal measures such as pharyngeal arch length (Fickling and Lee, 1981; McIntyre and Ward, 1986; Radke et

al., 2000), vertebral diameter (Pikhu and Pikhu, 1970; Feltham and Marquiss, 1989), and a variety of skeletal bones (Newsome, 1977; Hansel et al., 1988; Scharf et al., 1998) have been used to generate models for predicting original prey size.

The bluefish (*Pomatomus saltatrix*) is a voracious piscivore and is among the top predatory fish species in the western North Atlantic Ocean (Buckel et al., 1999). Bluefish are an important fish both commercially and recreationally, and over the past two decades stocks off the eastern coast of the United States have experienced a dramatic decline. From 1978 through 1996, the commercial landings and spawning stock biomass of bluefish declined by over 60% (Fahay et al.¹). A variety of mechanisms have been proposed to explain this dramatic decline, including intense predation by large apex predators. It is known that bluefish act as an important prey species for a number of apex predators in the North Atlantic, most notably the shortfin mako (*Isurus oxyrinchus*). Stillwell and Kohler (1982) sampled 399 makos from 1972–79 and found that bluefish made up 85% of the diet by volume. The mako diet has recently been reviewed and it appears that the incidence of bluefish in the diet has increased (assume 1 mL=1 g for flesh) to 94% of their diet by weight (Wood et al.²). Bluefish have also been found to be important in the diet of bluefin tuna (*Thunnus thynnus*) (Chase, 2002), swordfish (*Xiphias gladius*) (Stillwell and Kohler, 1985),

blue shark (*Prionace glauca*) (Kohler, 1989), and the thresher shark (*Alopias vulpinus*) (Kohler³).

The motivation for this study came from field sampling shortfin mako (*Isurus oxyrinchus*) stomach contents where it was observed that bluefish jaw bones and various other skull bones were often intact, even if the rest of the prey fish was digested. To generate accurate estimates of the original prey size a series of predictive equations was generated by regressing bluefish skull bone measurements with the fork length (FL) and total length (TL) of the fish. Five skull bones were chosen to obtain measurements for the relationships: the dentary, maxilla, premaxilla, opercle, and cleithrum (Fig. 1). These five bones were chosen because they are strong bones (with the exception of the opercle), covered by extensive musculature, and assumed to be resilient to digestion.

Materials and methods

During June–September of 2000 and 2001, bluefish were collected by rod and reel and by otter trawl in Narragansett Bay, RI, and at bluefish fishing tournaments along the northeast coast of the United States from Ocean

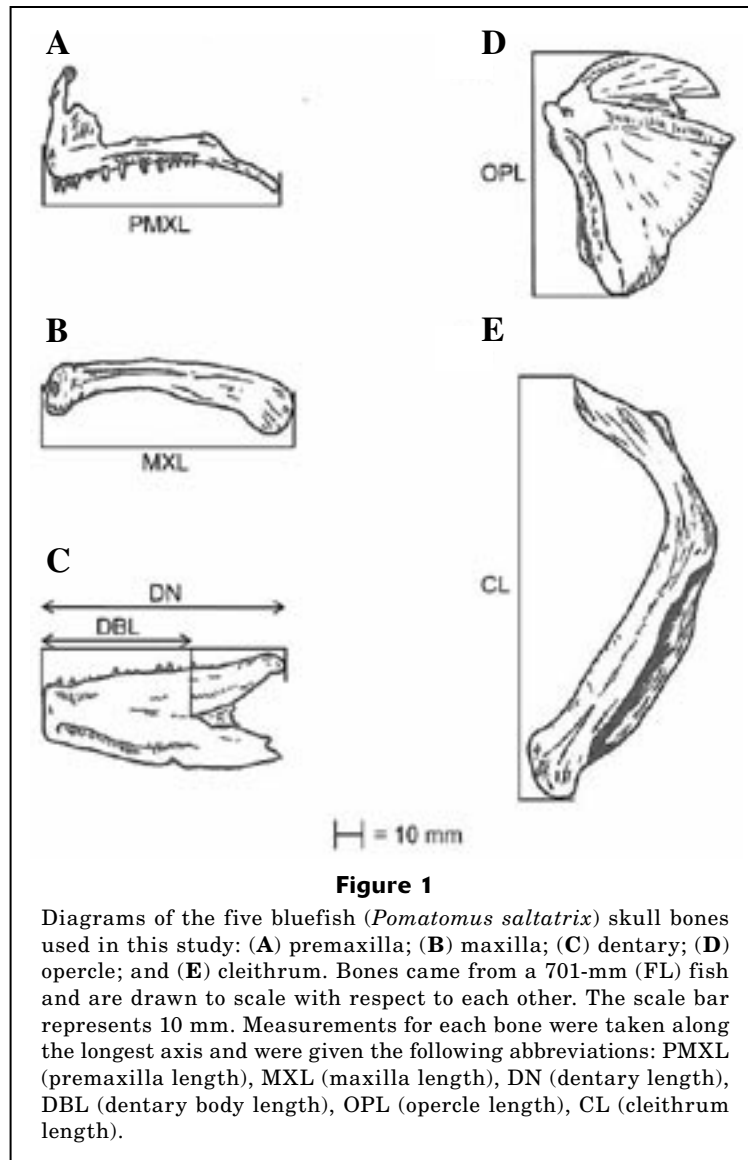
¹ Fahay, M. P., P. L. Berrien, D. L. Johnson, and W. W. Morse. 1999. Essential fish habitat source document: Bluefish, *Pomatomus saltatrix*, life history and habitat characteristics. NOAA Tech. Memo. NMFS-NE-144, 68 p. U.S. Department of Commerce, NOAA, NMFS-NEFSC, Woods Hole, MA.

² Wood, A. D., B. Wetherbee, N. E. Kohler, F. Juanes and C. Wilga. 2004. In prep. Predator prey interaction between the shortfin mako (*Isurus oxyrinchus*) and bluefish (*Pomatomus saltatrix*).

³ Kohler, N. E. 2001. Personal commun. NMFS Narragansett lab, 28 Tarzwell Drive, Narragansett, RI 02882.

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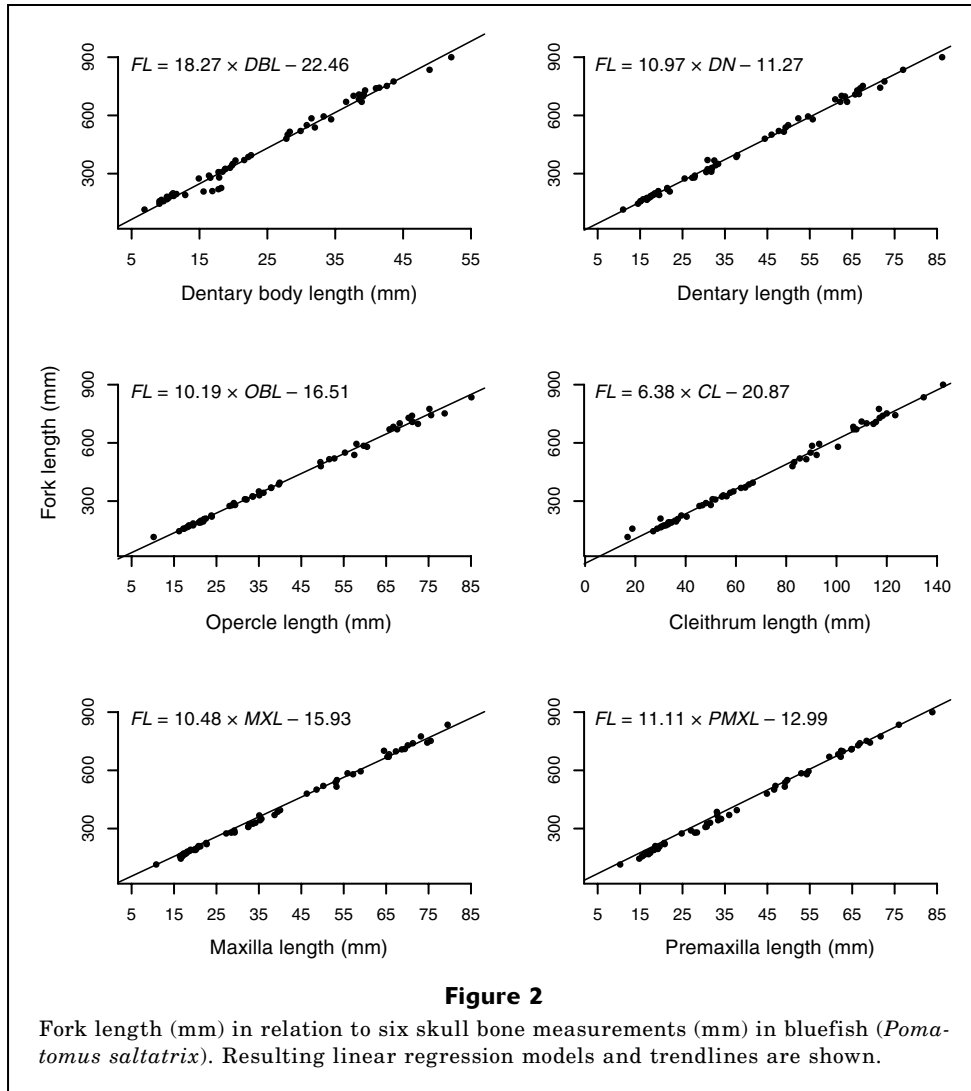
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City, MD, north to Bayshore, NY. Upon retrieval, the fork length (FL) and total length (TL) of each fish were measured to the closest mm. The heads of the bluefish were then removed by cutting approximately 5 cm behind the pectoral girdle, and all heads were immediately placed on ice. Samples were returned to the laboratory and kept in a cool room on ice until the selected bones could be extracted and measured (within 24 hours). Bones were extracted by immersing the bluefish heads in boiling water for a short period of time (between 30 and 180 seconds, depending on the size of the fish and on the amount of musculature around the bones). The dentary, maxilla, premaxilla, opercle, and cleithrum were dissected from the left side of each fish and measured to the nearest 0.1 mm by using 0–150 mm dial calipers. Measurements were taken linearly along the

longest axis of each bone and the following abbreviations were used to indicate lengths: DBL (dentary body length), DN (dentary length), OPL (opercle length), CL (cleithrum length), MXL (maxilla length), and PMXL (premaxilla length) (Fig. 1). In cases where left bones were damaged, or it was determined that an accurate measurement could not be retrieved, right-side bones were measured in place of the damaged bones.

Least squares regression analyses, which reveal the relationship of each of the bone measurements to FL and TL, were then conducted to generate predictive equations. The strength of each of the correlations was judged by both the r^2 values and by calculating the mean percent prediction error for each model, where the percent prediction error for a model (Sharf et. al., 1997) is calculated by the following equation:



$$\frac{(\text{Observed} - \text{Predicted})}{(\text{Predicted})} \times 100.$$

To determine if any one bone or set of bones provided the best predictor equation, comprehensive models involving sets of bones were fitted in a stepwise linear algorithm by using the Akaike information criterion (AIC) as the criterion for model selection. Models were generated in both a forwards and backwards manner in order to confirm that the same model was returned in all cases.

Results

Fork length (FL) and total length (TL) measurements were taken from 58 bluefish ranging from 110 mm to 900 mm FL. The resulting regression equations correlating skull bone measurements to FL (Fig. 2) were highly significant ($P=0.005$ for the dentary correlation and

$P<0.001$ for the rest of the models). The r^2 values for the FL predictive equations ranged from 0.988 to 0.997, and the mean percent predictive errors ranged from -0.03 to 1.19 (Table 1). Similarly, all of the resulting models correlating the bone measurements to total length (Fig. 3) were highly significant ($P<0.001$, r^2 values ranging from 0.987 to 0.996, and mean percent predictive errors ranging from -0.11 to 1.07 [Table 1]).

Bones were ranked from best predictor to worst predictor for both the FL and TL models by using the Akaike information criterion (AIC). In both cases the premaxilla was ranked the best predictor bone, followed by the maxilla, the opercle, the dentary, the cleithrum, and finally dentary body length. The bone measurements included in the stepwise multiple regression model for predicting fork length were PMXL, OPL, and DN (Table 2). In the best predictor model for total length, PMXL, OPL, DN and CL were included (Table 2).

Table 1

Resulting predictive equations of fork and total length in relation to several skull bone measures with corresponding coefficient of determination (r^2) and P -values, and mean percent predictive errors (%PE) for each model.

Bone	Fork length	r^2	P -value	%PE
Dentary body length (DBL)	$FL = 18.27(DBL) - 22.46$	0.988	<0.001	0.54
Dentary (DN)	$FL = 10.97(DN) - 11.27$	0.996	0.005	-0.03
Opercle (OPL)	$FL = 10.19(OPL) - 16.51$	0.997	<0.001	0.28
Cleithrum (CL)	$FL = 6.38(CL) - 20.87$	0.993	<0.001	1.19
Maxilla (MXL)	$FL = 10.48(MXL) - 15.93$	0.997	<0.001	0.31
Premaxilla (PMXL)	$FL = 11.11(PMXL) - 12.99$	0.997	<0.001	0.26
Bone	Total length	r^2	P -value	%PE
Dentary body length (DBL)	$TL = 20.20(DBL) - 27.69$	0.987	<0.001	0.46
Dentary (DN)	$TL = 12.13(DN) - 15.42$	0.996	<0.001	-0.11
Opercle (OPL)	$TL = 11.27(OPL) - 21.13$	0.996	<0.001	0.15
Cleithrum (CL)	$TL = 7.05(CL) - 26.13$	0.994	<0.001	1.07
Maxilla (MXL)	$TL = 11.59(MXL) - 20.43$	0.996	<0.001	0.19
Premaxilla (PMXL)	$TL = 12.28(PMXL) - 17.20$	0.996	<0.001	0.14

Table 2

Independent variables included in the stepwise linear regression models used to estimate original bluefish fork length and total length.

	Variables included in forward stepwise regression model	Variables included in backward stepwise regression model
Fork length	PMXL, OPL, DN	PMXL, OPL, DN
Total length	PMXL, OPL, DN, CL	PMXL, OPL, DN, CL

Discussion

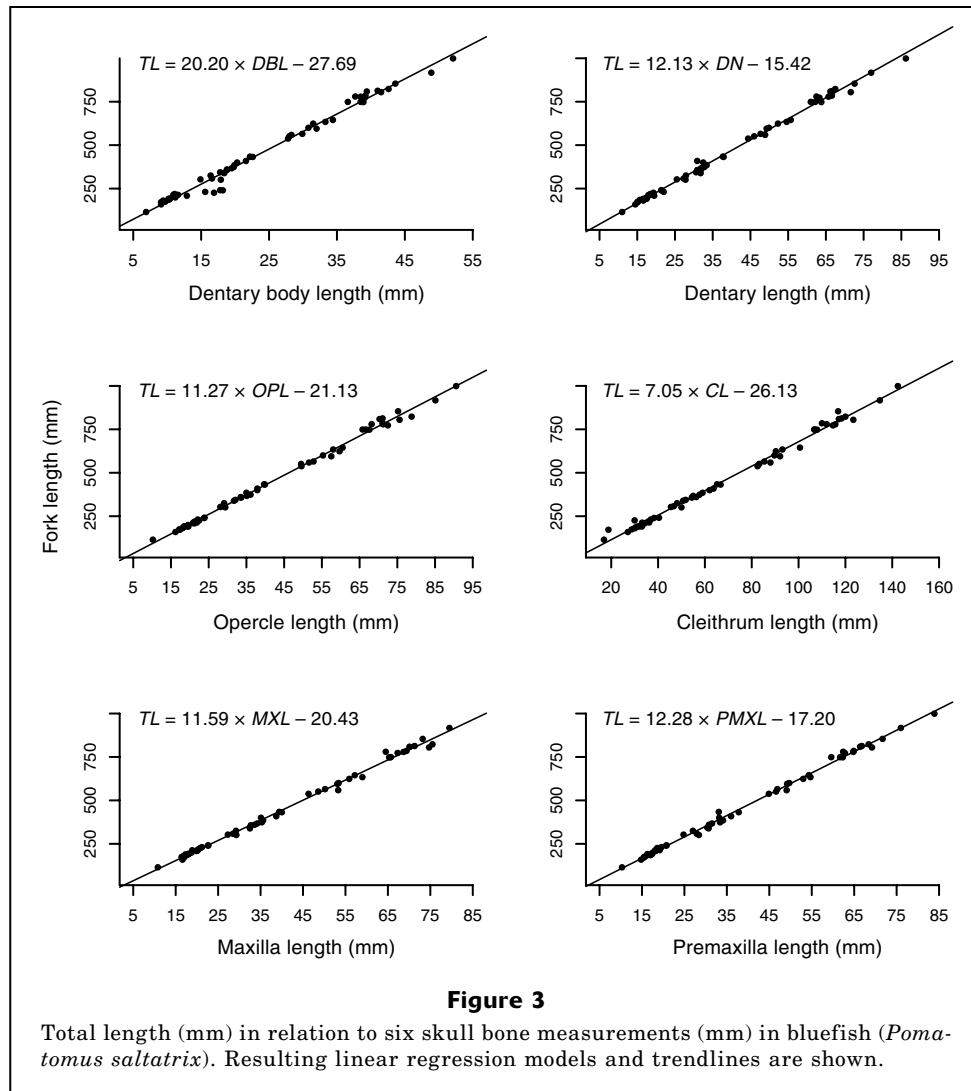
This study revealed that measurements of five skull bones can be used as accurate predictors of original fork length and total length of bluefish. Although the methods of other studies were incorporated in this study, the information is the first of its kind for bluefish and may serve as a tool for the future study of this species in the North Atlantic.

In recent years there has been growing concern over the stability of the bluefish stock and an increased effort to gather information on the possible mechanisms affecting bluefish abundance and distribution in the western North Atlantic.⁴ One of the proposed mecha-

nisms that could be adversely influencing the recovery of bluefish is top-down pressure by a number of apex predators in the North Atlantic. Although indiscriminant predation on bluefish may not be a significant pressure on the stock, size selective predation can dramatically alter the structure of the prey community (McIntyre and Ward, 1986; Trippel and Beamish, 1987; Sharf et al., 1997).

In order to study the consumption rates of key predators in an ecosystem it is necessary to gather information on the sizes of the prey being consumed (Elliot and Persson, 1978; Sharf et al., 1998). However, it is often difficult to estimate the original size of a prey item from stomach content data because of the complications caused by digestion. Erosion of the prey bones from digestive juices can lead to measurement error or bias when prey sizes are back-calculated from digested parts (Sharf et al., 1998). Although bias from digestion is a concern that should be addressed in studies, internal bones and hard parts of fishes have been shown to be excellent predictors of original prey size (Trippel and

⁴ In 1997 Rutgers University and the NMFS organized a workshop to study the factors that could be contributing to the depressed state of the bluefish stock. A similar concern was expressed by Congress at this time, and the Rutgers and NMFS workshop led to a request for proposals for bluefish-related research in 1998, 1999, and 2000.



Beamish, 1987; Hansel, 1988, Sharf et al., 1998). In addition, the bones used in the present study are strong bones (with the exception of the opercle), that are liable to resist digestive erosion.

All the relationships generated in the present study yielded very accurate predictions of original prey size, but the jaw bones are of special interest. Bluefish can be classified as predators that exhibit a biting behavior during predation. Fish that show this type of predation behavior have very heavy, robust jaw bones (Norton, 1995). The jaw bones (maxilla, premaxilla, and dentary) of bluefish are both easily identifiable and likely resistant to digestion, and when combined with the adequacy with which original size can be determined from these bones (based on AIC rankings and %PE), they are the best option for researchers interested in back-calculating original bluefish sizes.

The results of this study provide a means to further analyze the stomach contents of bluefish predators beyond identifying, and quantifying prey items.

The usefulness of this type of data has been shown repeatedly for a number of species (McIntyre and Ward, 1986; Feltham and Marquiss, 1989; Serafy et al., 1996; Sharf et al., 1997; Sharf et al., 1998). The ability to back-calculate the original size of a prey leads to the enhancement of diet studies and allows for more accurate estimates of predator consumption rates. The lack of this kind of data and correlations for many key prey species in the Atlantic and elsewhere is surprising.

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Literature cited

- Buckel, J. A., M. J. Fogarty, and D. O. Conover.
1999. Foraging habits of bluefish, *Pomatomus saltatrix*, on the U.S. east coast continental shelf. *Fish. Bull.* 97:758-775.
- Chase, B. C.
2002. Differences in diet of Atlantic bluefin tuna (*Thunnus thynnus*) at five seasonal feeding grounds on the New England continental shelf. *Fish. Bull.* 100:168-180.
- Crane, S. A., J. M. Fenaughty, and R. W. Gauldie.
1987. The relationship between eye diameter and fork length in the spiny oreo dory, *Allocyttus sp.* *N.Z.J. Mar. Freshw. Res.* 21:641-642.
- Elliott, J. M., and L. Persson.
1978. The estimation of daily rates of food consumption for fish. *J. Anim. Ecol.* 47:977-991.
- Feltham, M. J., and M. Marquiss.
1989. The use of first vertebrae in separating, and estimating the size of, trout (*Salmo trutta*) and salmon (*Salmo salar*) in bone remains. *J. Zool.* 219:113-122.
- Fickling, N. J., and R. L. G. Lee.
1981. Further aids to the reconstruction of digested prey lengths. *Fish Manage.* 12:107-110.
- Hansel, H. C., S. D. Duke, P. T. Lofy, and G. A. Gray.
1988. Use of diagnostic bones to identify and estimate original lengths of ingested prey fishes. *Trans. Am. Fish. Soc.* 117:55-62.
- Kohler, N.E.
1989. Aspects of the feeding ecology of the blue shark, *Prionace glauca*, in the western North Atlantic. *Diss. Abst. Int. Pt. B-Sci. & Eng.* 49:1-179.
- McIntyre, D. B., and F. J. Ward.
1986. Estimating fork lengths of fathead minnows, *Pimephales promelas*, from measurement of pharyngeal arches. *Can. J. Fish. Aquat. Sci.* 43:1294-1297.
- Newsome, G. E.
1977. Use of opercular bones to identify and estimate lengths of prey consumed by piscivores. *Can. J. Zool.* 55:733-736.
- Norton, S. F.
1995. A functional approach to ecomorphological patterns of feeding in cottid fishes. *Environ. Biol. Fishes* 44:61-78.
- Pikhu, E. Kh., and E. R. Pikhu.
1970. Reconstruction of the size of fishes swallowed by predators from fragments of their vertebral column. *J. Ichthyol. (USSR)*, vol. 10:706-709.
- Radke, R. J., T. Petzoldt, and C. Wolter.
2000. Suitability of pharyngeal bone measures commonly used for reconstruction of prey fish length. *J. Fish Biol.* 57:961-967.
- Scharf, F. S., J. A. Buckel, F. Juanes, and D. O. O'Connor.
1997. Estimating piscine prey size from partial remains: Testing for shifts in foraging mode by juvenile bluefish. *Environ. Biol. Fishes* 49:377-388.
- Scharf, F. S., R. M. Yetter, A. P. Summers, and F. Juanes.
1998. Enhancing diet analyses of piscivorous fishes in the northwest Atlantic through identification and reconstruction of original prey sizes from ingested remains. *Fish. Bull.* 96:575-588.
- Serafy, J. E., C. M. Schmitz, T. R. Capo, M. E. Clarke, and J. S. Ault.
1996. Total length estimation of red drum from head dimensions. *Prog. Fish-Cult.* 58:289-290.
- Stillwell, C. E., and N. E. Kohler.
1982. Food, Feeding Habits, and Estimates of Daily Ration of the Shortfin Mako (*Isurus oxyrinchus*) in the Northwest Atlantic. *Can. J. Fish. Aquat. Sci.* 39:407-414.
1985. Food and feeding ecology of the swordfish *Xiphias gladius* in the western North Atlantic Ocean with estimates of daily ration. *Mar. Ecol. Prog. Ser.* 22:239-247.
- Trippel, E. A., and F. W. H. Beamish.
1987. Characterizing piscivory from ingested remains. *Trans. Am. Fish. Soc.* 116:773-776.