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Research Article

Predicting Atlantic Bonefish (*Albula vulpes*) Fork Length From Head Morphometry

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This study developed predictive models using generalized linear statistical analyses to estimate Atlantic bonefish (*Albula vulpes*) fork length (FL) dependent on four head morphometry covariates: snout length, eye diameter, postorbital head length, and head length. A total of 257 South Florida bonefish were examined, which ranged from 28 to 720 mm FL. Each of the morphometric measurements was highly correlated with FL, with coefficients of determination (r^2) that ranged from 0.9592 for eye diameter to 0.9959 for head length. Total length (TL) was also highly correlated with FL. Sex differences in the morphometric measurements were examined; however, no significant sexual dimorphism was detected. All of the morphometric measurements examined were good predictors of Atlantic bonefish FL and TL.

Keywords: *Albula vulpes*; bonefish; morphometry; predicting length

1. Introduction

Atlantic bonefish (*Albula vulpes*) is an Elopiform species that inhabits tropical and subtropical coastal marine environments around the globe [1]. Bonefish are an important link in the food chain because they feed on benthic organisms (e.g., shrimp, snails, crabs, and small fish) [2] and, in turn, are prey for large predators (e.g., sharks, groupers, barracuda, and bottlenose dolphins) [3]. Bonefish also support lucrative regional economies through recreational fishing revenues [3]. The annual economic impact of the recreational fishery is US $50 million in Belize, US $169 million in the Bahamas, and US $465 million in Florida of the United States [4]. Bonefish fisheries are primarily catch-and-release with limited harvest and are considered a data-poor species. Currently, only one stock assessment has ever been conducted on a bonefish stock, and it was on the Florida's bonefish stock [5]. In the central western Atlantic (e.g., Florida and the Florida Keys, the Bahamas, and Cuba), bonefish are frequently attacked by predators (e.g., *Negaprion brevirostris*, *Carcharhinus leucas*, and *Sphyraena barracuda*) while being angled by fly-fishing or conventional hook-and-line gears. These encounters often result in the angler landing only the head of the bonefish and possibly some anterior parts of the body. The goal of this study was to develop predictive relationships that facilitate the quantification of bonefish body lengths with only head morphometry measures. Anticipating the need for accurate estimates of fork length (FL) and total length (TL) from head dimensions, following [6, 7], the paper provides statistical estimation equations for determining bonefish lengths when only the head is available.

2. Materials and Methods

A wide range of bonefish sizes was collected with hook-and-line and seine gears from South Florida waters as part of an age, growth, and stock assessment study [5]. FL and

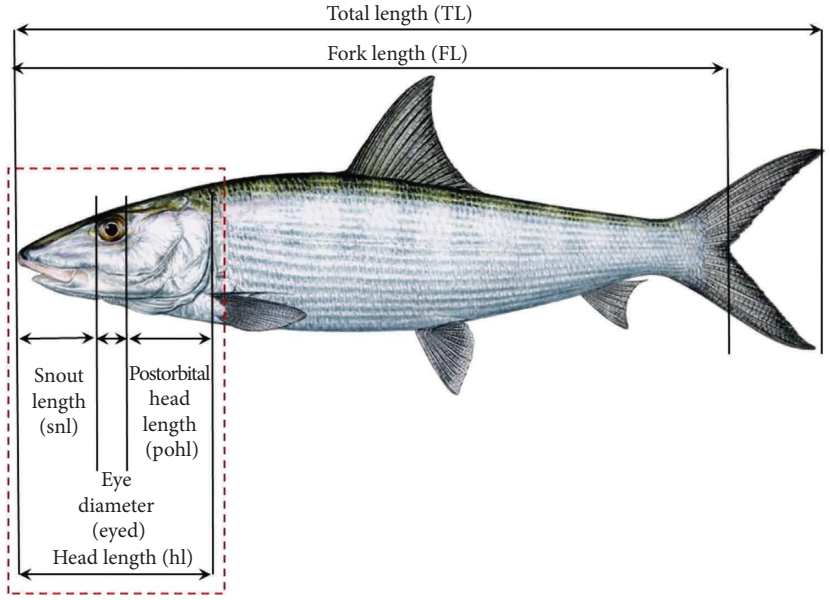

Figure 1: Definitions of Atlantic bonefish morphology measurements used in bonefish length prediction analyses. The four head metrics are shown in a red dashed box.

Table 1: Regression coefficients with standard errors in parentheses, coefficient of determination, and F-ratio fit statistics for the generalized linear regression estimation of fork length dependent on four Atlantic bonefish head morphometry dimensions (c.f., Figure 1) and also using total length to predict fork length.

	b_0	b_1	r^2	F	p
Head measurements					
Snout length	45.6654 (2.3010)	7.5890 (0.0513)	0.9885	21,906	$< 2.2e-16$
Eye diameter	−68.5904 (5.6879)	28.3160 (0.3656)	0.9592	6000	$< 2.2e-16$
Postorbital head length	21.5020 (2.0771)	8.6053 (0.0495)	0.9916	30,278	$< 2.2e-16$
Head length	16.9167 (1.4745)	3.5949 (0.0145)	0.9959	61,477	$< 2.2e-16$
Body measurements					
Total length	−7.6023 (0.9226)	0.8830 (0.0021)	0.9986	176,139	$< 2.2e-16$

Note: Coefficients b_0 and b_1 refer to the intercept and slope values following the equation of $Y = b_0 + b_1 X$, where Y is the fork length and X is the different measurement variables. All measurements are in mm. The degrees of freedom were 255 fish.

Table 2: Correlation matrix for the six principal morphometric variables used in this study.

	FL	TL	hl	poh1	snl	eyed
FL	1.0000	0.9993	0.9979	0.9958	0.9942	0.9794
TL		1.0000	0.9967	0.9942	0.9925	0.9814
hl			1.0000	0.9979	0.9976	0.9744
poh1				1.0000	0.9947	0.9712
snl					1.0000	0.9632
eyed						1.0000

Note: Morphometric variables are fork length (FL), total length (TL), head length (hl), postorbital head length (poh1), snout length (snl), and eye diameter (eyed).

a suite of morphometric measurements were recorded to the nearest millimeter with a Fisher Scientific Fisher-brand ruler. This present study focused on four bonefish morphometric head measurements: snout length, eye diameter, postorbital head length, and head length (Figure 1). Bonefish sex was also recorded when mature gonads were available. Due to the possibility of collecting different bonefish species in Florida waters, fin clips were taken from each bonefish and processed by the Florida Marine Research Institute (FMRI) for *Albula vulpes* species confirmation following the methods of [8]. The sampling of specimens in this study complied with United States Animal Welfare Act laws, guidelines, and polices as approved by the National Oceanic and Atmospheric Administration.

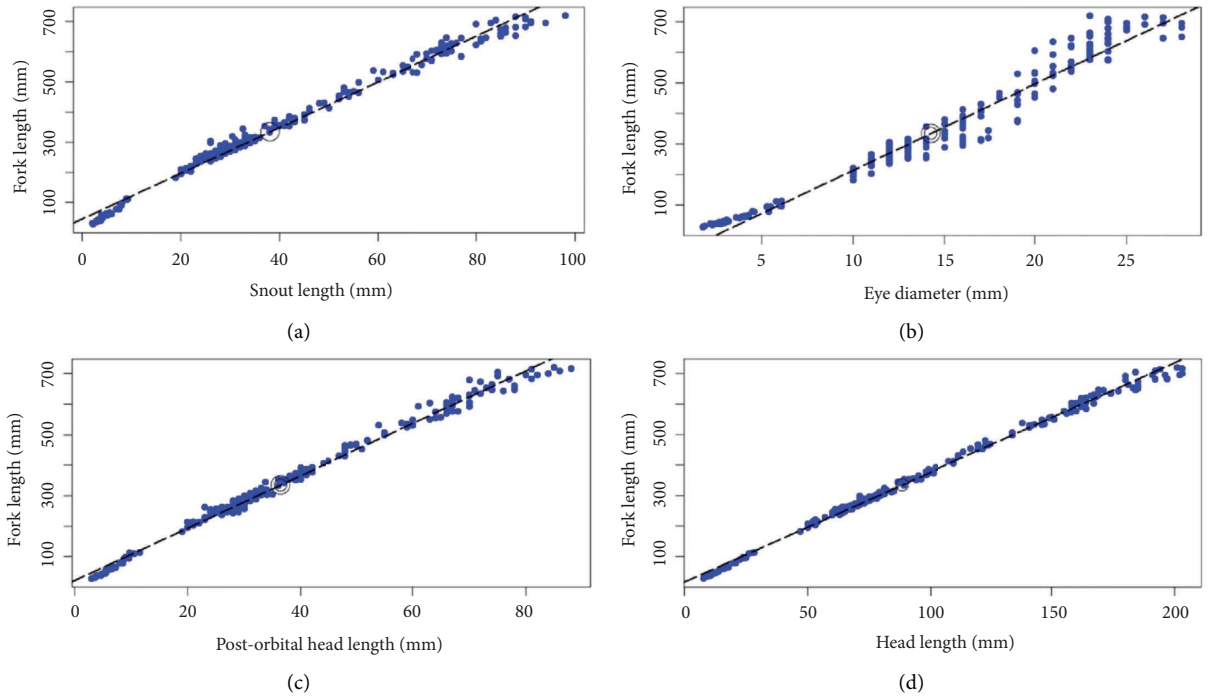

FIGURE 2: Generalized linear statistical model fits (dashed black line) to observed data (blue circles) for fork length dependent on (a) snout length, (b) eye diameter, (c) postorbital head length, and (d) head length.

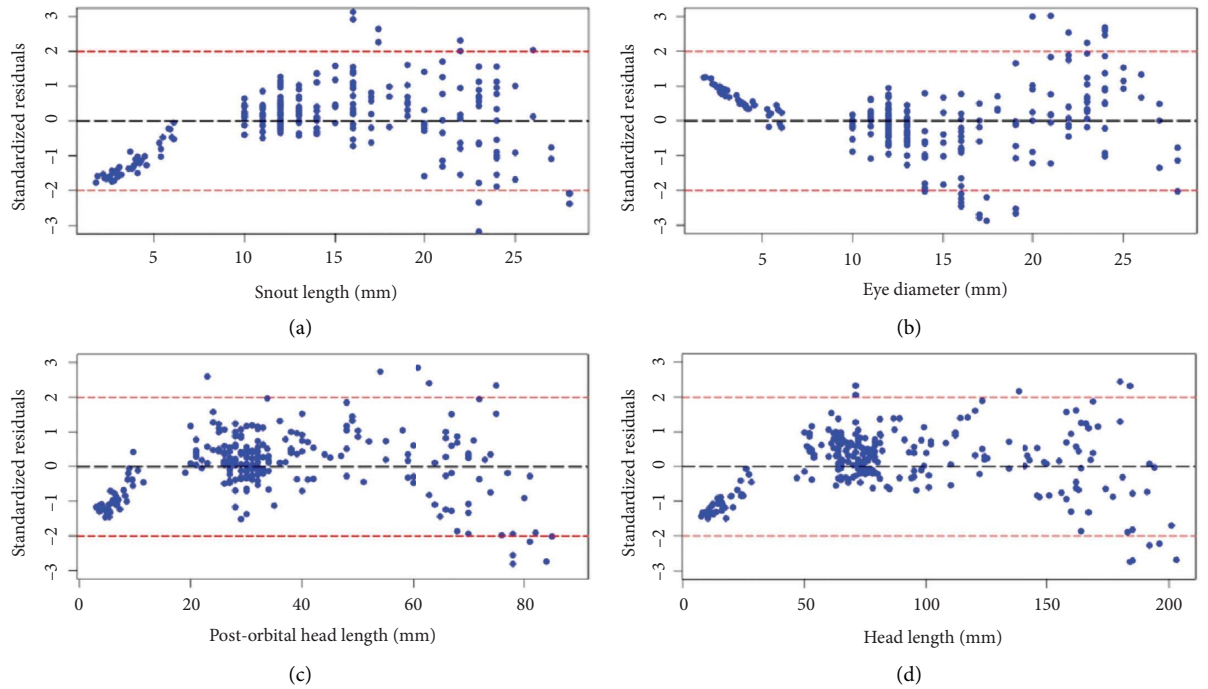

FIGURE 3: Continued.

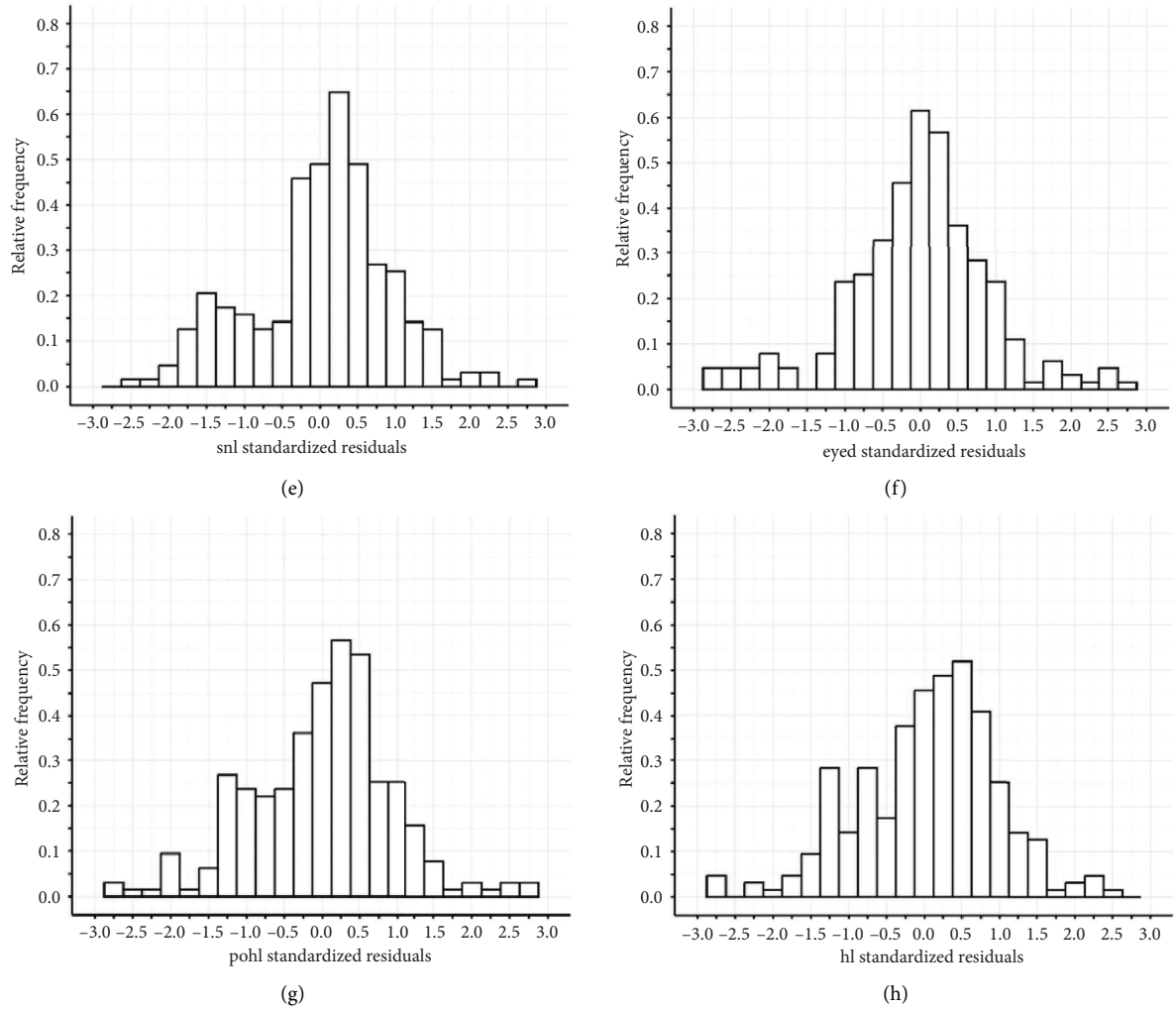

FIGURE 3: Regression diagnostics for the linear statistical model fits of fork length dependent on (a and e) snout length, (b and f) eye diameter, (c and g) postorbital head length, and (d and h) head length.

Generalized linear statistical regression methods [9–13] were used to generate several independent-variable models with *R* software [14, 15] following

$$Y_i = b_0 + b_1 X_{1i} + \cdots + b_k X_{ki} + \varepsilon_i, \quad (1)$$

where b_0 is the intercept, b_1 is the slope, and ε_i is the error term that is a normally distributed random variable. Several generalized linear statistical models were built following equation (1), where Y_i = FL and X_{ki} = head morphometric measurements or TL for covariate k. FL prediction models were created for each measurement. Analysis of covariance (ANCOVA) models were also developed to test for potential sexual dimorphism. Statistical comparisons were made at the $\alpha = 0.05$ level.

3. Results

From November 2003 to January 2010, a range of morphometric measurements were made for 257 bonefish ranging in size from 28 to 720 mm FL. These consisted of 53 females, 33 males, and 171 sexually immature individuals, or fish whose gonads were not available. All bonefish used in this study were confirmed as Atlantic bonefish, *Albula vulpes*, by FMRI genetic analyses. Pertinent generalized linear statistical model coefficients, associated fit statistics, and diagnostics are presented in Tables 1 and 2 and Figures 2, 3, and 4. Model coefficients of determination (r^2) ranged from 0.9592 to 0.9956 for the four head morphology measurements. Overall, the four head morphology measurements to FL relationships for all sexes combined were

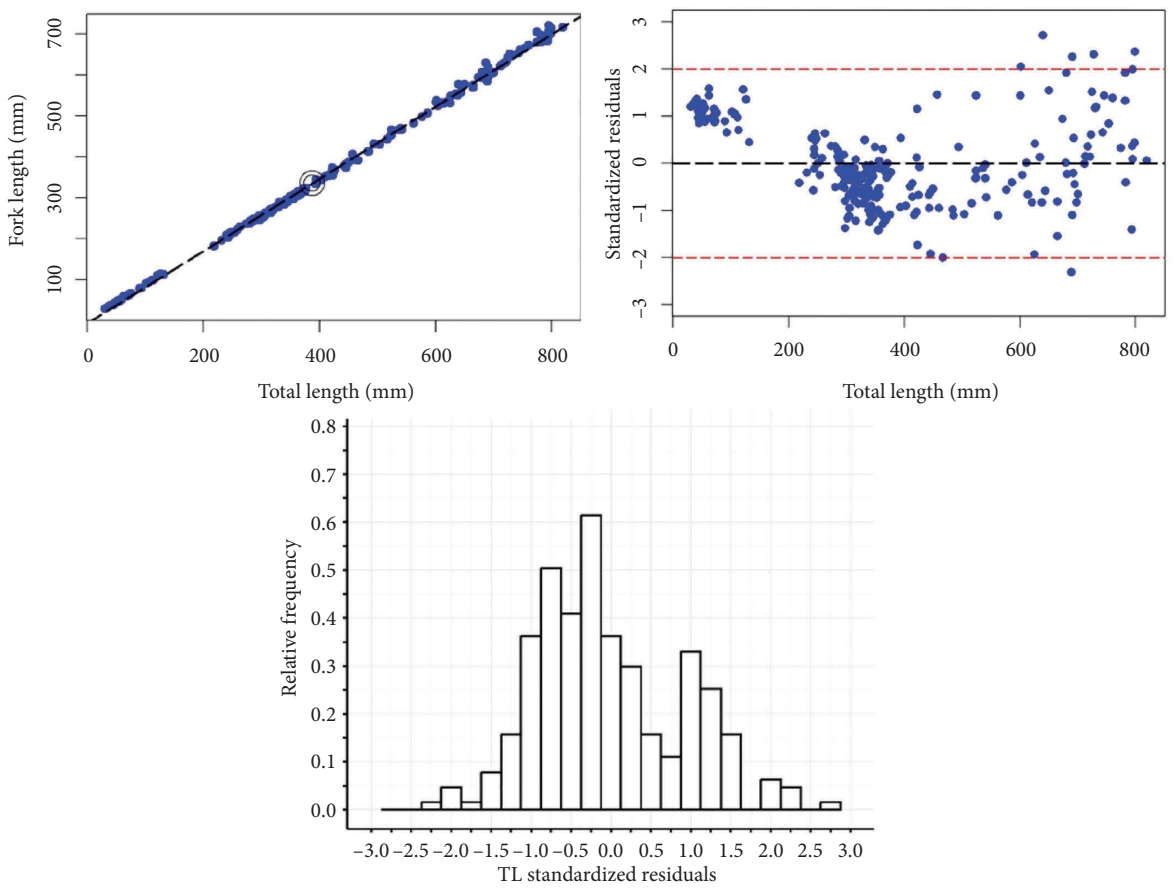

Figure 4: Regression fit and model diagnostics for the linear statistical model fit of fork length (FL) dependent on total length (TL).

Table 3: ANCOVA of potential sexual dimorphism in the length dependent on head morphometry analyses with 85 degrees of freedom.

	Intercept		Slope	
	F	*p*	*F*	*p*
Head measurements				
Snout length	0.3160	0.575	0.8790	0.351
Eye diameter	2.6500	0.108	0.0090	0.921
Postorbital head length	0.2550	0.615	0.0360	0.850
Head length	0.2870	0.594	0.9260	0.339

highly significant ($p < 0.001$). Predicting TL from FL had a model coefficient of determination of 0.9986 and was also highly significant ($p < 0.001$).

ANCOVA statistical comparisons of the morphometric measurements for both the intercept and the slope of the regression are shown in Table 3. No significantly different sexually dimorphic length dependent on head morphology relationships were detected for all four head measurements.

4. Discussion

All four head morphometric covariates examined were good predictors of FL. The head morphometric measurement with the highest accuracy of predicting FL was the head length measurement. FL and TL are highly correlated, and either could be accurately predicted from any of the four covariates. No statistical differences were detected between the sexes for all morphometric measurements evaluated. Therefore, there is no evidence of sexual dimorphism in bonefish morphometry for the measurements used in this study.

5. Conclusion

The study's results will be useful to both the recreational fishing and scientific communities. The fishing community will benefit by now having the ability to accurately estimate the length of a bonefish that was attacked by a predator during the fishing event when all the angler has is the bonefish's head. The scientific community can benefit by having the ability to obtain key measurements for age and growth research when only the bonefish head is available from which to extract the otoliths. The scientific community can also benefit from receiving additional length data that

can be used in analysis such as length-based assessment models. In fact, the assessment of Florida's bonefish stock used length data for a length-based stock assessment model [5]. In addition, length measurements can serve as proxies for a range of ecological and population dynamics attributes that are essential for the effective management of fish [16, 17].

Data Availability Statement

The data from this study's findings are available from the corresponding author upon request.

Ethics Statement

The sampling of specimens in this study complied with United States Animal Welfare Act laws, guidelines, and polices as approved by the National Oceanic and Atmospheric Administration.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Michael F. Larkin and Jerald S. Ault developed the concept for this study, conducted field work, generated data, assimilated the data, analyzed the data, and prepared the manuscript.

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