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A reliable game fish weight estimation model for Atlantic tarpon (*Megalops atlanticus*)

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This paper is dedicated to the memories of the late Billy Pate (IGFA Hall of Fame) and Capt. Joel Kalman.

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ABSTRACT

Rapid growth of popular and lucrative catch-and-release marine sportfisheries worldwide has highlighted the need for reliable weight estimation methods for use in fishing tournaments, pursuit of fishing records, and to support scientific research that allows captured fish to be released alive. This paper describes new methods to predict weight from measurements of body size of game fish. Here we also evaluated efficacy of a widely used historical model and compared this to several new statistical and analytical weight estimation models that we developed herein. We applied these candidate models to a unique morphometric data set on Atlantic tarpon (*Megalops atlanticus*) which contained information on body weight W as a function of fork length L and dorsal girth G for more than 1100 individuals from Florida, the Gulf of Mexico, Caribbean Sea and western Africa. A popular formula ($W = G^2 L/800$), developed more than a century ago specifically for tarpon was originally derived from geometric and physical relationships between fish body weight and shape. We found this model to be negatively biased >−15% (i.e., underestimates individual fish weights) across the tarpon's entire size range up to 130 kg (the current world record). Bias for our "new" ellipsoid volumetric formulation, which extends the principles of allometry, was less than 1% across the entire range of observed sizes. Our new estimator was used by Texas Parks and Wildlife Department to assist fishery management in setting "minimum maximum" sizes for recreationally caught tarpon that have the potential to break the Texas State record. It has also supported catch-and-release tarpon fisheries and tournaments in Florida, Texas, Mexico, and Trinidad. It provides a reliable means to accurately estimate weights of tarpon of potential (world) record sizes.

1. Introduction

Catch-and-release fishing has rapidly grown to become an economic force in marine sportfisheries (Bartholomew and Bohnsack, 2005; American Sportfishing Association, 2011). This growth of catch-and-release sportfishing represents a clear evolution of thinking for many fishers from an historical ethos of catch-and-consume (or hung up for photographs), to a decidedly more conservation-minded perspective that places minimum stress on the fish during the capture process, so that it can be released alive and survive. This conservation-ethic has become the primary goal of high-profile guides and anglers pursuing record catches of premier game fish such as Atlantic tarpon (*Megalops atlanticus*), billfish (Istiophoridae), bonefish (*Albula vulpes*) and permit (*Trachinotus falcatus*). Methods to conserve and sustain these magnificent resources for future generations have become a priority. As a consequence, there is great need for rapid and reliable weight estimation methods for fish caught by savvy amateur anglers in pursuit of world records, in big-money professional tournaments, and to support scientific research to build sustainable fisheries.

An important case in point is the Atlantic tarpon (*M. atlanticus*). For more than a century Tarpon have reigned as perhaps the world's most sought-after inshore saltwater game fish (Dimock, 1911; Babcock, 1921; Griswold, 1922; Breeder, 1944; Robins, 1977; Ault, 2008, 2010; Luo et al., 2008; Mill, 2010; IGFA, 2012). Few species can match the tarpon's strength, airborne acrobatics, or stamina. Today tarpon sportfishing in the Gulf of Mexico and southeastern U.S. supports an economic impact of $6 billion USD and 100,000 jobs. Popularity of the "*Silver King*" soared in the United States in the late 1930s when then-President Franklin D. Roosevelt battled tarpon off Port Aransas, Texas. But the excitement had really begun decades earlier through the legendary exploits of Charles F. Holder (1903), A.W. Dimock (1911), Zane Grey (1919), and F.G. Griswold (1921) in the Florida Keys and eastern Gulf of Mexico, and is widely documented in other writings (Gregg, 1902; Miller, 1931; Kaplan, 1937).

Tarpon are living descendents of a primitive lineage of teleost fishes (Robins and Ray, 1986); however, over the past 50 years the seascape for tarpon has changed dramatically. While stock

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assessment data and models for tarpon recreational fisheries compare miserably with those for directed commercial fisheries, there are obvious signs of trouble in many prominent historical fishing locations. For example, Port Aransas – once considered "*Tarpon Capital of the World*" – is now virtually devoid of the tarpon numbers that made it so famous (Ault, 2010). While tarpon were one of the first saltwater species to be declared a game fish (IGFA, 2012), today there is serious speculation concerning the root fishing and environmental causes for these declines. What is needed is a tool for estimation of fish weights in tournaments and for world records that encourages a more stringent conservation ethic of catch-and-release fishing practices.

In this paper we explore quantitative methods to accurately estimate the weight of individual Atlantic tarpon. We do so by analyzing the efficacy of an historical game fish weight estimation algorithm, and then through extended development of several general phenomenological (statistical) and mechanistic models, compare potential differences in regional sizes of fish and the statistical efficacy of the models to determine the most efficient methodology, and then explore their reliability for Atlantic tarpon.

2. Materials and methods

2.1. Distribution of tarpon sportfisheries

Population dynamics and resource ecology of Atlantic tarpon (Family Elopidae) are detailed in Ault et al. (2008a). Tarpon reach a relatively large size (to 140 kg and 250 cm FL), are highly migratory, and frequent coastal and inshore waters of the tropical and subtropical central Atlantic Ocean (Robins and Ray, 1986; Ault, 2008), but they may also transit pelagic waters during their extensive seasonal migrations (Ault, 2010). Tarpon are the focus of highly valuable regional sport fisheries throughout their range. Tarpon in the western Atlantic range from Nova Scotia to Brazil (Robins and Ray, 1986), but particularly the entire Gulf of Mexico, Florida Keys to Virginia, Bermuda, coasts of Central America and the Caribbean Sea (Wade, 1962), and more recently the eastern Pacific near the terminus of the Panama Canal. In the eastern Atlantic, tarpon occur primarily along the coasts of Angola to Senegal (Roux, 1960), but rarely from Portugal, the Azores, southern France to northern Spain (Arronte et al., 2004). The genetic connections of the species are not well understood, but recent migration studies shown population linkages between Mexico, the Gulf of Mexico and the southeastern United States (Ault, 2010).

2.2. Data assimilation

The specific and hypothetical morphometry of an Atlantic tarpon used for model development is shown in Fig. 1. Morphometric data were accurate measurements of body weight W in kg, and fork length L and dorsal girth G in cm. These data were obtained from several reliable sources: the Florida Fish and Wildlife Conservation Commission ($n = 1407$; Crabtree et al., 1995, 1997); the International Game Fish Association (IGFA) world record database ($n = 73$; IGFA, 2012); and, recreational tarpon tournaments from the Bay of Campeche ($n = 136$; in particular, Veracruz and Coatzacoalcos Yacht Clubs) during the period 2000–2011 (Fig. 2).

2.3. Assessment of model performance

Fish weight is largely determined by body volume (shape) and the inherent mass of its skin, tissue and bones. What is less clear is the form of the function that best describes the mean relationship between some simple to measure external features of the fish (e.g., L and G) and W (Ricker, 1975; Rohlf and Marcus, 1993; Quinn and Deriso, 1999). In this section we build statistical and analytical

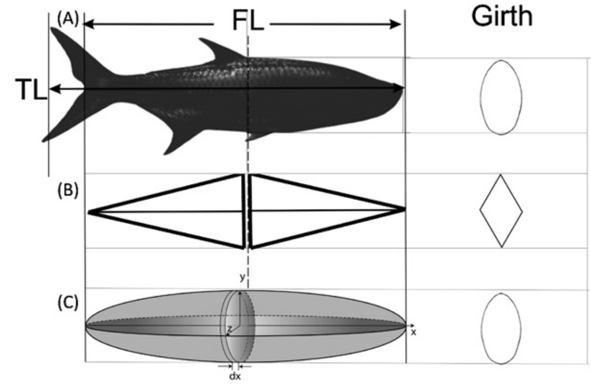

Fig. 1. Geometric relationships between individual body morphometry and volume and (weight) for Atlantic tarpon: (A) lateral view of natural observed Atlantic tarpon body geometry showing location of dorsal girth G (dashed line) just ahead of dorsal fin and associated cross-section (at approximately 50% of fork length L); (B) tarpon geometry approximated by Wood's (Eq. (6)) formula; and (C) tarpon geometry approximated by ellipsoidal calculus used to derive the new nonlinear volume model (Eq. (11)), where $x = L$, and y and z relate to the elliptical components of girth G.

models to estimate fish weight that use predictor values $x_1, \ldots, x_n$ response values $y_1, \ldots, y_n$ and a given mean function f depending upon some unknown parameters. To judge the efficacy of a particular model fit, the parameter estimates are determined as the parameters providing the best fit of the mean function f to the observations $y_1, \ldots, y_n$ obtained by minimization of the residual sum of squares (RSS) with respect to the parameters β

$$\mathrm{RSS}(\beta) = \sum_{i=1}^{n} (y_i - f(x_i, \beta))^2 \quad (1)$$

The minimization of RSS is often referred to as minimizing the least-squares criterion, and the solution to the minimization

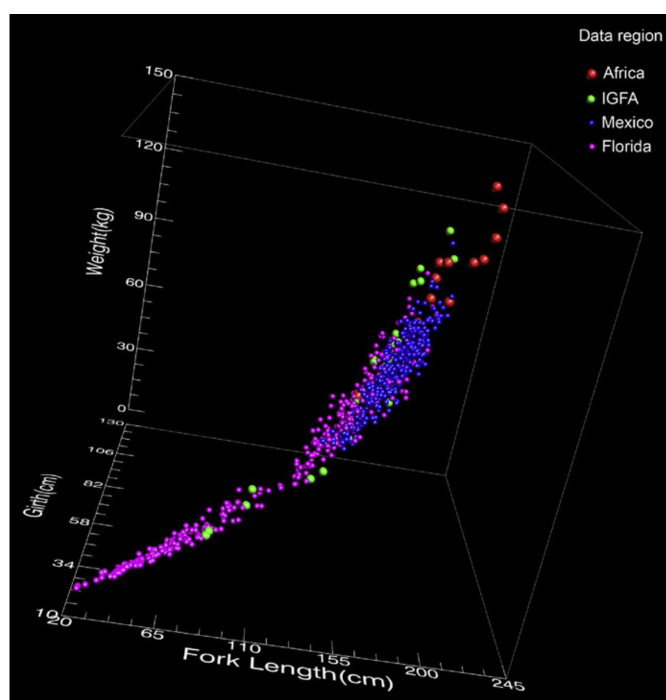

Fig. 2. Distribution of tarpon weight (kg) data as a function of fork length (L) and dorsal girth (G): $W = f(L, G)$ used for GLM estimation. Data regions are indicated by the colors of the spheres.

problem is the least squares estimates $\hat{\beta}$. These estimates are the β values (within the domain of all β values that are meaningful for a given mean function *f*) that make RSS as small as possible. For problems with nonlinear mean functions *f*, the minimization of RSS will in general be a nonlinear problem that will require specific numerical optimization methods (Ritz and Streibig, 2008).

2.3.1. Conversion to common size units

We standardized the unit length measure for our analyses to fork length (*L*) because of the relative ease of accurate measurements. However, total length (TL) was collected routinely by IGFA, so there was need to convert historical TL measurements to reliable estimates of *L*, given $y_i = L_i = f(\mathrm{TL}_i)$ is an appropriate first-order generalized linear model of the form

$$y_i = f(x_i; \beta) = L_i = b_0 + b_1 \mathrm{TL}_i + \xi_i \tag{2}$$

where x_i is data, β (i.e., b_0 and b_1) are model parameters to be estimated, and ξ_i is a normally distributed error term with N (0, σ^2).

2.3.2. Regional growth variability

Tarpon data used in the various weight estimation models came from a number of sources around the Gulf of Mexico, Caribbean Sea and Africa. To test the hypothesis that tarpon measurements obtained from the various geographical sources had regional differences in observed growth, and thus should probably be treated independently, principal component analysis (PCA) was used (Johnson and Wichern, 2002; Borcard et al., 2011). PCA reduced the original data set containing a large number of variables to a data set containing few new variables, but that nevertheless represent a large fraction of the variability contained in the original data set. Because principal components depend solely on the population covariance matrix, their development does not require a multivariate normal assumption. On the other hand, principal components derived for multivariate normal populations have useful interpretation in terms of constant density ellipsoids. To ensure this statistical property we used $\log_e$ transformed data for the PCA.

2.3.3. Model 1: Allometric growth

A simple and widely used relationship in quantitative fishery science is the allometric function. It is well known that within any life stanza of a fish, body weight *W* varies as some power function of length or related body measure (Ricker, 1975; Quinn and Deriso, 1999)

$$W_i = b_0 L_i^{b_1} \xi_i \tag{3}$$

where W_i is body weight, L_i is fork length, and b_0 is a scalar coefficient while b_1 is the "power" coefficient of the weight dependent on length function. Eq. (3) is "intrinsically linear" (Kutner et al., 2005; De Robertis and Williams, 2008), such that a simple transformation (e.g., natural logarithmic) renders a linear statistical model

$$\log_e(W_i) = \log_e(b_0) + b_1 \log_e(L_i) + \xi_i \tag{4}$$

Ordinary least squares regression is used to obtain initial parameter estimates for Eq. (4); these starting values that can be employed to formally fit Eq. (3) using nonlinear least squares analysis (Draper and Smith, 1998; Hastie et al., 2001; Faraway, 2004; Fox, 2008). In these analyses we fit Eq. (3) using both fork length *L* and girth *G* as predictor variables of weight.

2.3.4. Model 2: Wood's historical geometric formulation

A popular historical formulation to estimate the weight of marine game fish weigh, due William W. Wood (Babcock, 1921; Griswold, 1922; Breeder, 1944; Heilner, 1953) — a pioneer of tarpon fishing, was developed by a simple geometric assumption about the shape of a fish and its relationship to body weight. Assume that tarpon's observed volume (Fig. 1A) can be approximated by two wedges placed base to base (Fig. 1B). Thus, the combined volume (cubic inches) of the body would be equal to the area of the base multiplied by the length of one of the wedges.

To see this, assume that the base of the wedge is a square of unit length 1 on each side. The circumference *G* (perimeter length around the base) or idealized "girth" is $G = 1 + 1 + 1 + 1 = 4$. Girth is a square rotated at 45 degrees. Squaring the circumference produces one that is 16 times the area of the original square, since the area *A* (base of the wedge) is $A = 1 \times 1 = 1$. So, if $G^2 = 16$, and $A = G^2/16$, then the cubic volume V (in.^{3}) of the fish = area × (1/2) length, i.e.,

$$V = \frac{G^2}{16} \times \frac{L}{2} = \frac{G^2 L}{32} \tag{5}$$

The displacement of water by a unit volume of fish requires the specific gravity of a fish (i.e., consisting of bones, organs and flesh), which is approximately 1.11. Thus, 25 in.^{3} of fish volume weighs about 1 pound (Pennycuick, 1988). Dividing the volume of the fish approximated by Eq. (5) by 25 gives the fish's weight in pounds

$$W = \frac{G^2}{16} \times \frac{L}{2} \times \frac{1}{25} = \frac{G^2 \times L}{800} \tag{6}$$

2.3.5. Model 3: Generalized multivariate linear statistical model

The empirical observations of weight *W*, fork length *L* and girth *G* were fit a generalized multivariate linear model (GLM; Fox, 2008; Faraway, 2004, 2006; Wright and London, 2009; Petris et al., 2009)

$$Y_i = b_0 + b_1 X_{1i} + b_2 X_{2i} + b_{11} X_{1i}^2 + b_{22} X_{2i}^2 + b_{12} X_{1i} X_{2i} + \xi_i \tag{7}$$

where $N(0, \sigma^2)$. Data were log-log transformed (see De Robertis and Williams, 2008), and step-wise regression procedures were used to produce the GLM

$$\log_e(W_i) = b_0 + b_1 \log_e(L_i) + b_2 \log_e(G_i) + \log_e(\xi_i) \tag{8}$$

where $\log_e(W_i)$ is natural logarithm of weight kg of the *i*th observation, $\log_e(L_i)$ is natural logarithm of fork length in cm, is $\log_e(G_i)$ natural logarithm of dorsal girth in cm, and ξ_i is the lognormal error term. Model form was determined using the forwards-backwards-all possible regressions method of Kutner et al. (2005). Standard diagnostics (e.g., distribution and trends in residuals, leverage, etc.) were used to evaluate the efficacy of the regression model fits (Kutner et al., 2005; Fox, 2008; Dalgaard, 2008).

2.3.6. Model 4: Ault-Luo Ellipsoid (ALE) model

We endeavored to develop a more mechanistic model that specifically accounted for weight as a function of tarpon body volume (i.e., fork length and girth) by assuming that it was best represented by an ellipsoid (Fig. 1C)

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \tag{9}$$

where a is a function of fork length ($a = (L/2) + \xi_1$), b is a function of girth ($b = (G/2\pi) \times \kappa_2 + \xi_2$), c is proportional to b ($c = b \times \kappa_1$), and ξ_1, ξ_2 are normally distributed measurement error terms. The volume (V) of the ellipsoid is

$$V = \pi \frac{4}{3} abc \tag{10}$$

Assume ρ is the density of fish; then, the weight of a fish (W) can be thus solved for as

$$\begin{aligned} W = \quad \rho V &= \rho\pi\kappa_1 \frac{4}{3} b^2 a = \rho\pi\kappa_1 \frac{4}{3}\left(\frac{G}{2\pi}\times\kappa_2+\xi_2\right)^2\left(\frac{L}{2}+\xi_1\right) \\ &= \rho\pi\kappa_1\frac{4}{3}(a_0G+\xi_2)^2\left(\frac{L}{2}+\xi_1\right) \\ &= \rho\pi\kappa_1\frac{4}{3}(a_0^2G^2+2a_0G\xi_2+\xi_2^2)\left(\frac{L}{2}+\xi_1\right) \\ &= \rho\pi\kappa_1\frac{2}{3}a_0^2G^2L+\rho\pi\kappa_1\frac{4}{3}a_0\xi_2GL+\rho\pi\kappa_1\frac{2}{3}\xi_2^2L \\ &\quad +\rho\pi\kappa_1\frac{4}{3}a_0^2\xi_1G^2 \\ &\quad +\rho\pi\kappa_1\frac{4}{3}a_0\xi_1\xi_2G+\rho\pi\kappa_1\frac{4}{3}\xi_2^2\xi_1L \end{aligned}$$

$$W = b_0 + b_1G^2L + b_2GL + b_3G^2 + b_4G + b_5L \quad (11)$$

The Ault-Luo ellipsoid (ALE) model, Eq. (11), was fit to both a nonlinear least squares algorithm and a generalized linear model, given the apparent linearity of its analytical solution. All statistical analyses were conducted using the R Project for Statistical Computing software (http://www.r-project.org/). Two-dimensional contour isopleths and three-dimensional model surface plots were generated using FORTRAN numerical algorithms linked to the IDL (Interactive Data Language) scientific visualization software (ITT Visual Information Solutions, http://www.ittvis.com/).

3. Results

The new ALE model (Eq. (11)) produced the minimum residual sum of squares error (RSS) and was therefore the best model fit (Table 1); followed by the loglinear GLM (Eq. (8)), the nonlinear allometric on L and on G (Eqs. (3) and (4)), and Wood's geometric (Eq. (6)) models. It was not surprising that the ALE model was the most reliable and robust predictive model, since it is derived from mechanistic principles that most closely approximate the fundamental ellipsoid geometry shape of a tarpon. By in large, the other models were derived from purely phenomenological (statistical) or over-simplified mechanistic approximations.

Not all sample data had all the measurements (W, L, G) required for this study; however, we were able to convert the TL to L via Eq. (2). In the final model analysis, we had a total of 1072 samples of TL and L pairs, and 889 samples triplets of W, L and G (Table 1). Of the 889 triplet samples, these were grouped them into 4 regions (Fig. 2): Florida $n = 434$; Mexico $n = 417$; west Africa $n = 14$; and, IGFA $n = 24$ (Fig. 2).

3.1. PCA of regional tarpon measurements

Principal components analysis (PCA) was used to evaluate potential differences in body morphometry existed by region in the various measurement data bases. PCA showed that 99.8% of the variation of the data set was captured in the first principal component. We concluded that the major differences in morphometry observed were between juvenile and mature fish, and that no differences by region could be detected. Separation in body morphometry occurs at about 150 cm FL and 30 kg, which corresponded to the size of 100% sexual maturity of tarpon (Crabtree et al., 1997; Ault et al., 2008a). Western African tarpon (eastern Atlantic) appear to grow in the same allometric fashion as western Atlantic tarpon.

3.2. Allometric growth

While L and G are correlated, W is what will be observed in fishery data and is the statistic that coverts abundance to stock biomass

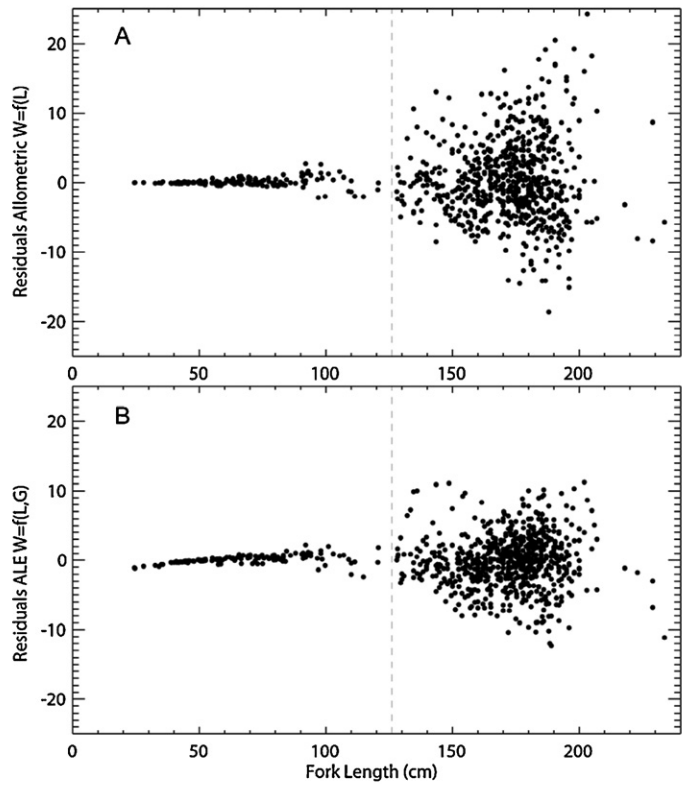

Fig. 3. Relationship of model residuals as a function of fork length (L) for: (A) allometric model (Eq. (3)); and (B) ALE model (Eq. (11)) weight estimation. The dashed line at 126 cm L indicates the size of 50% sexual maturity (Crabtree et al., 1997).

(Quinn and Deriso, 1999). It is well known that female tarpon grow to a larger size than males, i.e., dimorphic growth (Crabtree et al., 1997; Ault et al., 2008a). Therefore, in general the weight of fish should be a function of age, sex, fork length and girth [i.e., $W = f(a, sex, L, G)$]. However, the sex variable is mostly not available in standard fishery reporting data, and age must be determined indirectly by reading rings on otoliths. Observed discontinuity (Fig. 3A) in residuals at approximately 130 cm L is most likely a result of the unaccounted sex variable that corresponds to the onset of sexual maturity at 126 cm (size of 50% sexual maturity, Crabtree et al., 1997; Ault et al., 2008a).

3.3. Wood's model

Tarpon weight estimation using the Woods formulation (Eq. (6)) was negatively biased on average by more than 15% (Fig. 4A). This estimation error resulted from an over-simplification of tarpon body geometry. This was acceptable historically, but with big money tournaments and world record potential, this is no longer the case. Thus, to eliminate this dilemma, here we provide a reliable new estimator for gauging the weight of the tarpon you catch.

3.4. Multivariate statistical models

The log-linear multivariate statistical model (Eq. (8)) produced the second lowest RSS (Table 1). Since it is a statistical model, higher order terms were ignored because partial F-tests revealed that their inclusion into the model did not significantly reduce the mean squared error. The model produced accurate weight estimates shown by the distribution of relative error of predicted weights given L and G, such that more than 95 percent of all predicted weights are within ±1% of the true weight over the tarpon size range of 25–235 cm L. Statistically, this result is robust. However,

Table 1
Parameter estimates for the various Atlantic tarpon weight prediction model equations. *RSS* is the model residual sum of squares, *df* is degrees of freedom, R^2 is the approximate coefficient of determination.

Model	Equation	*df*	b_0	b_1	b_2	b_3	b_4	b_5	RSS	R^2
TL = *f*(*L*)	(2)	1072	−1.062607	0.896584						0.9997
Null deviance		889							508,041	0.0000
Wood geometric	(6)	889							57,091	0.8876
NL Allometric, *W* = *f*(*G*)	(4a)	887	0.001060709	2.41871487					39,609	0.9220
NL Allometric, *W* = *f*(*L*)	(4b)	887	0.0000182242	2.89265					23,127	0.9545
LL GLM, *W* = *f*(*L*, *G*)	(8)	886	−10.68070	1.93403	1.04958				9906	0.9805
ALE, *W* = *f*(*L*, *G*)	(11)	883	2.828	0.0000296	0.006123	−0.008284	0.1845	−0.1943	9747	0.9808

the model formulation is phenomenological and does not represent the mechanisms that define body shape and volume of the tarpon.

3.5. Ault-Luo Ellipsoid model

The Ault-Luo ellipsoid (ALE) model (Eq. (11)) produced the lowest RSS (Table 1), and quite acceptable diagnostics (Figs. 3B and 4B). The ALE model limited the residuals after the onset of sexual maturity at 126 cm *L* to much smaller and constant levels as compared to the allometric model (Fig. 3). The ALE model was derived on the basis of the fundamental mathematical geometry of an ellipsoid. It incorporated six parameters to describe the complex body shape of the tarpon. Statistically, only four of the six were significant (Table 1), but to preserve its mathematical form we retained all six parameters to produce a chart of a prediction isopleths of body weight (*W* in kg and pounds) as a function of fork length (*L*) and dorsal girth (*G*) for the Atlantic tarpon (Fig. 5). This chart can be easily used by anglers to estimate the weight of their catch. We have produced and distributed the chart at tarpon fishing tournament around world, and it has been proven a success, and saving hundreds, thousands of tarpon from unnecessary kills.

4. Discussion

4.1. Allometry models and model fit

Much of the progress of growth studies over the past three-quarters of a century has been related to the application of principles of body allometry (Jolicoeur, 1963; Gunderson, 1993; Ault et al., 1998, 2005, 2008a,b; Cibert et al., 1999; Sang et al., 2009). In fact, size-based methods are now widely used in the arsenal of modern stock assessment methods (e.g., Ault et al., 1998, 2005, 2008b; Quinn and Deriso, 1999; Gedamke and Hoenig, 2006). One of the most serious statistical limitations of the usual form of the allometry equation (Eq. (3)) is the way it should be extended to more than two dimensions. In this paper we focused development of improved weight estimation prediction through enhanced analysis of tarpon morphometrics as they relate to body volume and mass, using mathematical modeling and multivariate statistical analysis of shape variation within and among samples of organisms as a result of growth (Rohlf and Marcus, 1993). Here we provided a reliable new estimator for gauging the weight of the tarpon you catch without a need to hang it from a scale. The new ellipsoid weight model (Eq. (11)) developed in this study significantly improved the historical model of Wood (presented in Heilner, 1953). Other models we examined were either purely phenomenological (statistical) or over-simplified geometric approximations of tarpon body volume. For example, tarpon weight estimation by the Woods formulation (Eq. (6)) was on average negatively biased by more than 15% resulting from an over-simplification of tarpon body geometry. While this level of estimation error may have been previously acceptable, with big money tournaments and world record potentials on the line, this is no longer the case.

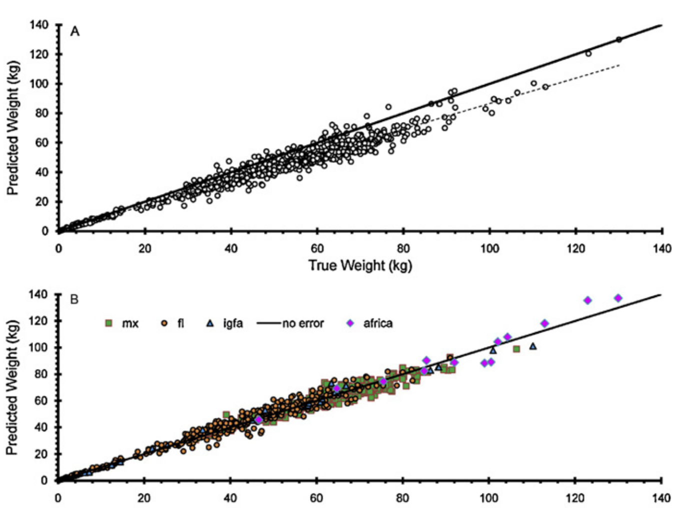

Fig. 4. Predicted weights $\hat{W}_i$ dependent on observed weights W_i (kg) for Atlantic tarpon (*Megalops atlanticus*) using: (A) the Wood's formulation (Eq. (6); open circles) and estimated mean regression (dotted line); and (B) the ALE model (Eq. (11)). The true unbiased weight is shown as a solid 45° line.

Bias of our "new" formulation was less than 1% across the entire range of observed sizes, whereas the historical Wood's model bias averaged >15% that increased with size. The ellipsoid model was the most reliable estimator because it most closely approximates the fundamental ellipsoid geometry of tarpon shape that defines body volume that is highly correlated with body weight. One cannot expect unanimity of opinion as to whose method is most effective, but there is consensus among most workers that it is important to take geometry into account (Rohlf and Marcus, 1993).

Length alone can be a relatively effective predictor of weight before sexual maturity as indicated by the small residuals (Fig. 3); however, after sexual maturity residuals increased drastically as a function of length (Fig. 3A). However, by using both length and girth, we were able to constrain the residuals to much lower ad relatively constant levels (Fig. 3B). A fundamental reason underlying the improvement in weight estimation provided by our new formulation is that the relationship between *W* and *L* and *G* indicates to us that early in life during the immature life stages when the marginal change in length with respect to time is greatest and change in girth is proportional to the length, *L* is a relatively good predictor of body weight. However, as the fish ages to reach sexual maturity, d*L*/d*t* decreases monotonically with changes in girth *G* (d*G*/d*t*) becoming less correlated to the length and more to the sex and the reproductive condition of the individuals, thus girth becomes more related to body weight. We believe that much of these changes have to do with demographic processes in that early-life gains in length favor predator avoidance, while adult gains in girth clearly enhance reproductive capacity.

At present there is a paucity of parallel data on African tarpon from the eastern Atlantic Ocean, but similarities in allometric

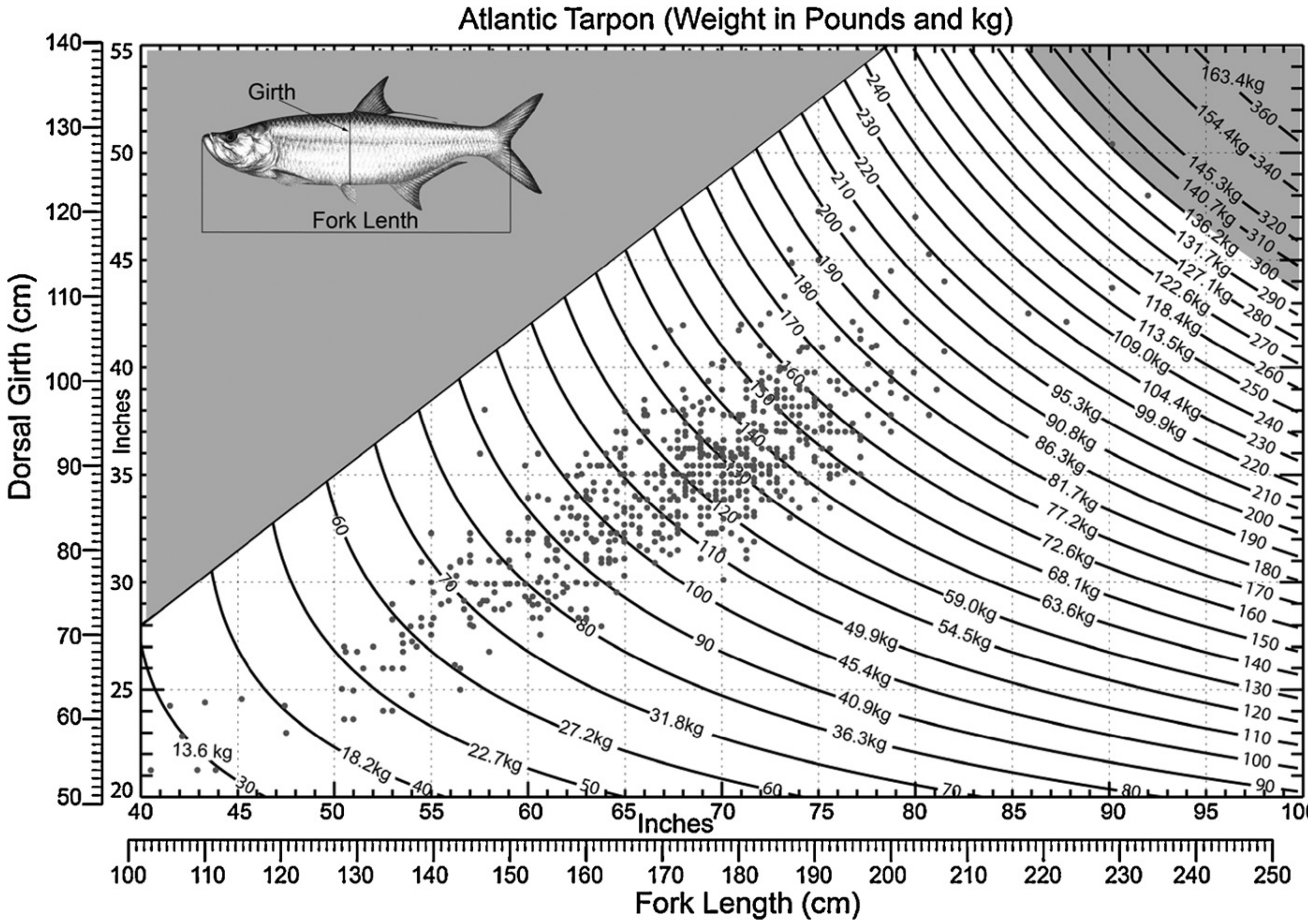

Fig. 5. Prediction isopleths of body weight *W* (kg and pounds) dependent on fork length *L* and dorsal girth *G* for Atlantic tarpon from the best-fit nonlinear volume model (Eq. (11)) in both metric and English. The solid dots are the samples used in the study, and the shaded area in the upper right hand side indicates potential all-tackle world record territory.

relations for what data exists. There is also potential genetic similarity and possible links to South America and the Caribbean Sea. There remains a lack sufficient age-and-growth data for tarpon around the region and a great need to increase sampling intensity around the "unit" spatial distribution of the resource by age/size. This would also involve invoking comprehensive sampling that supports advanced genomics methods.

4.2. Reliable weight estimation

The new ALE model provides a reliable basis for estimating the weight of a live tarpon. The regression range is for a fish weighing between 10 kg to the world record weight of about 150 kg. The model addresses two principal questions asked by sports fishermen: (1) How big was that tarpon I just caught? (2) How big do tarpon get (or how much does the largest tarpon weigh)? The answer to that first question is provided in Fig. 5 that provides two-dimensional contour prediction isopleths for body weight *W* (kg and pounds) dependent on fork length *L* and dorsal girth *G* for Atlantic tarpon from the best-fit nonlinear volume model (Eq. (11)). The shaded area in the upper right hand side indicates potential new all-tackle world record territory. Some insight into that second question is provided in Table 2. A review of the records can give us a sense of how big tarpon might get (IGFA, 2012). The International Game Fish Association (IGFA) database for tarpon registers the all-tackle world record at a weight of 130 kg (286.9 pounds). Tarpon larger than 300 pounds have been reported taken in artisanal fishermen's nets off Africa!

4.3. Resource management applications

The new ALE estimator is also a useful tool for resource management. Our estimator has been used in Texas to set minimum-maximum sizes of tarpon that have potential to break State angling records. It has gained support in catch-and-release tarpon fisheries and tarpon fishing tournaments, and provides a reliable means to accurately estimate potential tarpon is of (world) record size. For example, the current Texas State record for all tackle is 95.5 kg (210 pounds). Using the ALE model, to break or tie that record, a tarpon has to be measured with minimum fork length of 190 cm (with girth of 130 cm), or minimum girth of 90 cm (with length of 240 cm).

While Wood's formula was specifically developed for tarpon (Griswold, 1922), it has been indiscriminately applied to other deep-bodied fishes such as the channel bass (i.e., redfish), striped bass (*Morone saxatilis*), and salmon (*Oncorhyncus* sp.) and has been reported to work reasonably well for other, even though no empirical test of its efficacy has ever been performed. However, we found that the Wood's formula is strongly biased for tarpon. What is the consequence of such a bias? A funny and perhaps tragic story surfaced after the development of my new formula. It comes from Belize. A couple of anglers had caught what they believed to be a world record fish on a fly one bright day on the water. They used

Table 2
Rod-and-reel angling records for Atlantic tarpon from around the southeastern Atlantic, Gulf of Mexico, central American and Caribbean Sea, and western Africa. Data are from tournaments, State records and IGFA world-record databases. N/A is data not available.

Location	Weight (kg)	Date caught	Angler
SE Atlantic, Gulf of Mexico and Northern Atlantic			
Virginia	58.97	September 1975	Barry Truitt
North Carolina	87.68	September 2008	Malcolm Condie
South Carolina	70.13	September 2008	S.B. Kiser
Georgia	73.03	July 1995	C. Edwards
Florida Keys	110.22	February 1975	Gus Bell
Alabama	92.08	August 1992	Billy Wildeberger
Mississippi	75.75	May 2001	Keith Goodfellow
Louisiana	104.33	August 1993	Tom Gibson
Texas	95.57	October 2006	Jeremy Ebert
New Jersey	24.04	1982	Jim Klaczkiewicz
Cork, Ireland	32.66	October 1983	E. Twomey
Central America and Caribbean Sea			
Mexico	112.04	March 1938	Harry Sedgewick
Bahamas	N/A		
Cuba	70.99	April 2011	Stephan Dombaj
Dominican Republic	N/A		
Puerto Rico	39.01	November 2005	Ariana Cruz Mattei
Belize	74.84	August 2000	Anthony Cuomo
Honduras	58.06	July 2002	Amanda Noviello
Nicaragua	64.64	January 2009	Dr. Jerry Ault
Costa Rica	93.89	November 1994	Dan Wise
Panama	N/A		
Colombia	109.91	January 1955	Alfonsse Salazar
Venezuela	128.37	March 1956	Mario Salazar
Trinidad	89.81	August 2012	Jimmy Aboud
French Guyana	114.12	August 1990	Victor Boriandeni
Brazil	N/A		
U.S. Virgin Islands	8.62	December 1998	Darcy Loveland
Western Africa			
Senegal	N/A		
Guinea Bissau	130.00	March 2003	Max Domecq
Guinea	N/A		
Sierra Leone	128.50	April 1991	Yvon Sebag
Gabon	118.84	December 1990	Thomas Gibson
Congo	105.18	April 2012	Daniel Lopuszanski
Angola	64.68	February 2006	Alex Nicolson
Gambia	91.63	March 1998	Alberto Hernandez
Nigeria	97.07	January 1953	John Zarpas

the Wood's formula to estimate weight and decided that their large tarpon was under the record by a number of pounds. Upon arriving back at the lodge and reporting their catch, they were asked if they had used the new "Ault formula" for weight estimation. To their chagrin, the ALE formula showed that they had returned what would have been the new world record to the sea without properly documenting their catch!

4.4. Extended applications

The quantitative and analytical methods developed in this paper have now become part of the regional tarpon tournament fishing circuit (e.g., Texas Tarpon Tomorrow Pro-Am, Grand Isle Tarpon Rodeo, Boca Grande World's Richest, Florida Keys Golden Fly, South Carolina Low Country, Trinidad (British West Indies), etc.). The ALE estimator can be applied more generally in any (sport) fishery (such as billfish tournaments) where a biostatistical sampling program has collected the requisite morphometric data in a statistically rigorous way. Fishes with elliptical body shapes like bonefish (*A. vulpes*), tunas, etc., would seem to be likely additional candidates for applications. We hope that the results presented here will encourage fishing tournament organizers, promoters and sponsors to convert "catch-and-kill" tournaments to the conservational practice of "catch-and-release" tournaments around the world.

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