


MANAGEMENT BRIEF

Use of Gizzard Diameter to Estimate Weight and Length of Partly Digested Gizzard Shad in Piscivore Diets

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Abstract

In diet studies, stomach contents from predatory fish may be difficult to identify due to digestion. The Gizzard Shad *Dorosoma cepedianum* is an important prey species for sport fish; thus, determining the size of ingested shad can assist with evaluating competitive interactions, bioenergetic patterns, and niche partitioning and can add precision to predictive models. The gizzard organ of clupeids appears to be more resistant to digestion compared to other tissues and can often be found in the stomachs of predatory fish after other tissues from Gizzard Shad are digested. If the gizzard diameter is proportional to Gizzard Shad weight or length, it could be a useful structure for estimating the size of partially digested Gizzard Shad when other structures that are traditionally used to estimate weight or length (e.g., backbones) are damaged due to advanced digestion. For this reason, we evaluated the allometry relating gizzard diameter and Gizzard Shad weight and TL. We sampled a total of 936 Gizzard Shad from nine Oklahoma reservoirs. Fish were frozen and later thawed; they were measured for weight (± 0.01 g) and TL (± 1 mm), and the gizzard was then removed. Gizzard diameter was measured (± 0.1 mm) at its widest point using calipers. Eight different equations were evaluated to find the best relationship (lowest Akaike's information criterion) between gizzard diameter and weight or length. The relationship between gizzard diameter and fish weight was best modeled as a

second-order polynomial, whereas the relationship between gizzard diameter and fish TL was best described by a five-parameter Richard's equation. Both relationships explained over 80% of the variation in Gizzard Shad size. The 95% CIs for weight (± 4 –7%) and TL (± 2 –7%) indicated good overall precision for mean fish size based on gizzard diameter. Therefore, we recommend using gizzard diameter to determine weight and TL from diet samples when advanced digestion of Gizzard Shad limits the use of more traditional metrics (TL, backbone length, etc.).

Diet studies are central to fish ecology and fisheries management. Diet information is necessary to evaluate competitive interactions (Werner and Hall 1977; Keast 1978; Sutton and Ney 2002), bioenergetic patterns (Werner et al. 1996; Gauthier and Boisclair 1997; Sutton and Ney 2001), and potential growth issues caused by mismatches between predator demand and prey availability (Cyterski et al. 2002; Raborn et al. 2007; Evans et al. 2014). For a given species, the prey types common in the diet can vary from system to system due to differences in prey availability or habitat (Bettoli et al. 1992; Diehl

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1993; Shoup and Wahl 2009), making diet studies important even for well-studied species.

Fish diets are often determined by analyzing stomach contents, but prey found in stomachs can be macerated or partially digested, making it necessary to rely on digestion-resistant parts of the prey to identify stomach contents (Garvey and Chipps 2012). These digestion-resistant structures often have allometric relationships with prey weight or length that can be used to estimate the predigested size of the prey item (Wahl and Stein 1991; Benke et al. 1999; Shoup and Lane 2015). This not only is useful when the prey item is too digested to measure directly, but also can provide more accurate diet indices (e.g., percent composition by weight) than weighing the remains directly, as direct diet weights can bias weight-based indices toward digestion-resistant prey types.

Gizzard Shad *Dorosoma cepedianum* are important prey for many piscivores throughout the southern and central United States. The Gizzard Shad is often the most abundant prey species in many systems (Johnson et al. 1988; Stein et al. 1995) and is one of the most commonly eaten prey types for many predators (Noble 1981; Storck 1986; Johnson et al. 1988). As such, Gizzard Shad are often encountered in diet studies. Partially digested Gizzard Shad are often identified by the lack of spiny fins and the presence of a muscular gizzard near the esophagus that appears to be digestion-resistant enough to persist even when the rest of the body is too digested to identify (Bryant and Morais 1970; Storck 1986; Cyterski et al. 2002; Raborn et al. 2003; Denlinger et al. 2006). Previous studies of Gizzard Shad have found proportionality between gizzard size and fish TL that could be used to predict prey size from heavily digested individuals (Bryant and Morais 1970; Storck 1986), but these regressions were from single populations, had relatively small sample sizes, and only covered a narrow range of Gizzard Shad sizes (i.e., they would not be suitable for use with diets of larger piscivores, such as Striped Bass *Morone saxatilis*, ictalurids, esocids, etc.). Furthermore, proportionality between gizzard size and Gizzard Shad weight has not been explored, but if such a relationship exists it would be useful for diet studies. The purpose of this study was to evaluate the allometry relating gizzard diameter and Gizzard Shad weight and TL across several populations to determine whether it is useful for estimating Gizzard Shad weight and length in diet studies.

METHODS

We sampled a total of 936 Gizzard Shad from nine Oklahoma reservoirs (Arcadia Lake: $n = 79$; Canton Lake: $n = 99$; Lake Carl Etling: $n = 240$; Lake Evans Chambers: $n = 31$; Guthrie Lake: $n = 112$; Lake Elmer: $n = 110$; Sooner Lake: $n = 79$; New Spiro Lake: $n = 58$; Lake Thunderbird: $n = 128$) using 60-pulses/s DC electrofishing from July 2015

through June 2018. Fish were frozen until processed at a later date. Sampled Gizzard Shad ranged from 52 to 379 mm TL and from 1.7 to 720.6 g. Fish were thawed, weighed (± 0.01 g), and measured (± 1 mm), and the gizzard was dissected from each fish. Maximum gizzard diameter (i.e., diameter at the gizzard’s widest point perpendicular to the path of the esophagus through the gizzard) was measured (± 0.1 mm) using a Pittsburgh digital caliper (Model 47257; Griffon Corporation, New York; accuracy: ± 0.03 mm).

Eight different equations were evaluated to find the best relationship relating gizzard diameter with the weight and TL of individual Gizzard Shad. Evaluated functions included five linear or curvilinear relationships (linear, exponential, power, second-order polynomial, and third-order polynomial functions) and three sigmoidal curves (logistic equation, four-parameter Richard’s equation, and five-parameter Richard’s equation; Table 1). Tested equations were selected based on initial plotting of the data, which suggested a curvilinear or sigmoidal relationship, as well as including equation types that had been previously used to relate gizzard size with Gizzard Shad TL (i.e., polynomial and linear models; Bryant and Morais 1970; Storck 1986). All equations were fitted using the nlsLM() function of the minpack.lm package in R (Elzhov et al. 2016), and Akaike’s information criterion (AIC) was used to evaluate which model was most supported by the data. Diagnostic plots of the top model were visually evaluated to ensure that there were no patterns in the residuals that would indicate a lack of fit. The proportion of variation in weight or TL explained by gizzard diameter was calculated as the Nagelkerke pseudo- R^2 using the nagelkerke() function of the rcompanion package (Mangiafico 2020).

TABLE 1. Equations used to evaluate the relationship between maximum gizzard diameter (mm) and weight (g) or TL (mm) of Gizzard Shad (Y = response variable [weight or TL]; X = gizzard diameter; $a, b, c, d,$ and f = constants; e = base of natural logarithms).

Equation type	Function
Linear	$Y = a \cdot X + b$
Power	$Y = a \cdot X^b$
Exponential	$Y = a \cdot e^{(b \cdot X)}$
Second-order polynomial	$Y = a \cdot X + b \cdot X^2 + c$
Third-order polynomial	$Y = a \cdot X + b \cdot X^2 + c \cdot X^3 + d$
Logistic	$Y = \frac{b}{c + e^{(a \cdot X)}}$
Four-parameter Richard’s	$Y = a \cdot \left\{ 1 + (b - 1) \cdot e^{\left[-k \cdot \frac{X - c}{d(1 - d)} \right]} \right\}^{\left(\frac{1}{1 - a} \right)}$
Five-parameter Richard’s	$Y = a + \frac{b}{(1 + \{c \cdot e^{-d \cdot (X - f)}\})^{(1/c)}}$

We calculated 95% CIs and 95% prediction intervals via Monte Carlo simulation for each best-fit equation with the predictNLS() function of the propagate package (Spiess 2018) using 10,000 simulations.

RESULTS

In total, 936 Gizzard Shad (TL = 52–379 mm; weight = 1.7–720.6 g) were collected for this study. Gizzard Shad weight was best described as a second-order polynomial fit with gizzard diameter (Table 2; Figure 1; AIC weight = 0.66). The next best model was a third-order polynomial with an AIC value that was 1.89 units greater (indicating that it had similar support), but we chose to use the second-order polynomial equation because it was simpler, the slope of the cubic term in the third-order polynomial model was not significant, and residual analysis suggested that the second-order polynomial model provided a slightly better fit. All other models had AIC values over 4 units greater than that of the second-order polynomial model. The best-fit equation predicting Gizzard Shad weight (g) from gizzard diameter (mm) was

$$\text{Weight} = -9.28074 \cdot \text{gizzard diameter} + 1.00245 \cdot (\text{gizzard diameter})^2 + 23.6403.$$

The second-order polynomial equation had a pseudo- R^2 of 0.814, suggesting reasonable power for predicting Gizzard Shad weight. The 95% CI of the relationship had a vertical

range of 7–52 g, with relatively good precision across all gizzard diameters evaluated (Figure 1). Prediction intervals were fairly consistent, with a vertical range of 172–179 g.

The seven largest gizzard diameters in the Gizzard Shad length regression (triangles in Figure 2) did not fit the pattern observed in the rest of the data. All eight equations tested had strong patterns in the residuals related to these seven data points. Plotting these data points produced a roughly horizontal relationship between gizzard diameter and fish size, indicating that gizzards this large had little relationship with Gizzard Shad TL. Furthermore, these seven gizzards were taken from fish exceeding 360 mm TL—sizes that are rarely consumed even by large predators. Therefore, we only analyzed data from fish with gizzard diameters of 25.1 mm or less to omit these seven outlier data points.

With the seven largest gizzard diameters omitted, the relationship between gizzard diameter and Gizzard Shad TL was well described by a five-parameter Richard’s equation (Table 2; Figure 2; AIC weight = 0.92). The next best model was the logistic curve, which had an AIC value over 5 units greater than that of the five-parameter Richard’s equation. The five-parameter Richard’s equation for predicting Gizzard Shad TL was

$$\text{TL} = 61.46144 + \left[\frac{293.9346}{(1 + \{-0.36745 \cdot e^{[-0.13532 \cdot (\text{gizzard diameter} - 10.09833)]})\})^{(1/-0.36745)}} \right].$$

TABLE 2. Fit statistics for models predicting either Gizzard Shad weight (g) or TL (mm) from maximum gizzard diameter (mm; AIC = Akaike’s information criterion; ΔAIC = difference in AIC between the given model and the best-fit model; LogLik = log-likelihood; ΔLogLik = difference in log-likelihood between the given model and the worst-fit model; weight = Akaike weight; pseudo- R^2 = Nagelkerke pseudo- R^2). Models are arranged in order of increasing AIC.

Model type	AIC	ΔAIC	LogLik	ΔLogLik	df	Weight	Pseudo- R^2
Models predicting weight							
Second-order polynomial	9,733.3	0.0	-4,862.6	1,110.9	4	0.661	0.814
Third-order polynomial	9,735.2	1.9	-4,862.6	1,111.0	5	0.256	0.814
Five-parameter Richard’s	9,737.4	4.1	-4,862.7	1,110.8	6	0.083	0.814
Logistic	9,758.4	25.1	-4,875.2	1,098.4	4	0.000	0.747
Exponential	9,936.7	203.4	-4,965.3	1,008.2	3	0.000	0.809
Linear	10,175.3	442.1	-5,084.7	888.9	3	0.000	0.701
Four-parameter Richard’s	10,480.8	747.6	-5,235.4	738.1	5	0.000	0.587
Power	11,953.1	2,219.8	-5,973.5	0.0	3	0.000	0.000
Models predicting TL							
Five-parameter Richard’s	8,806.7	0.0	-4,397.3	194.0	6	0.923	0.868
Logistic	8,812.4	5.7	-4,402.2	189.2	4	0.054	0.866
Four-parameter Richard’s	8,814.1	7.4	-4,402.1	189.3	5	0.023	0.866
Third-order polynomial	8,821.7	15.1	-4,405.9	185.5	5	0.000	0.865
Second-order polynomial	8,847.2	40.5	-4,419.6	171.8	4	0.000	0.861
Power	8,862.4	55.7	-4,428.2	163.1	3	0.000	0.859
Linear	8,866.4	59.7	-4,430.2	161.2	3	0.000	0.858
Exponential	9,188.7	382.0	-4,591.3	0.0	3	0.000	0.799

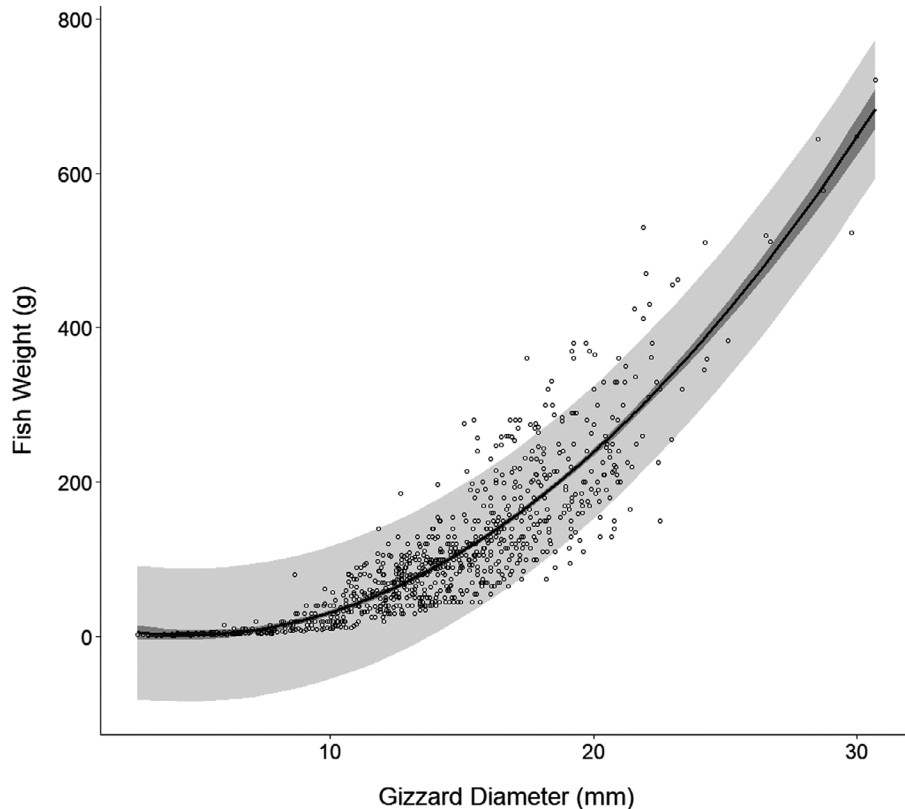


FIGURE 1. Best-fit model (second-order polynomial, selected from the eight models tested; Table 1) relating maximum gizzard diameter to Gizzard Shad weight. Modeled data are from 936 Gizzard Shad sampled from nine reservoirs in Oklahoma. The dark gray band is the 95% CI of the mean, and the lighter gray band is the 95% prediction interval.

The five-parameter Richard's equation had a pseudo- R^2 value of 0.867, suggesting reasonable predictive power. The 95% CI had a vertical range of 12–33 mm, with most portions of the CI exhibiting a vertical range between 20 and 25 mm. The 95% prediction interval had a vertical range of 109–113 mm.

DISCUSSION

We found that gizzard diameter was a good predictor of Gizzard Shad weight and length. Previously published regression equations predicting prey weight or length using other allometric relationships typically have explained 76–99% of the variation in prey size for fish prey (Wahl and Stein 1991; Raborn et al. 2002) and 35–99% of the variation in prey size for invertebrate prey (Smock 1980; Benke et al. 1999). Our nonlinear modeling function (nls[] function in R) cannot produce a traditional R^2 value because it optimizes parameters via maximum likelihood rather than ordinary least squares, but pseudo- R^2 values for both models were over 0.80 (i.e., pseudo- R^2 is a corrected ratio of the likelihood from the full model divided by the likelihood of a model with only a y -intercept as a way to evaluate the proportional improvement of the

fitted model parameters over the prediction of an intercept-only model). Although caution should be used in making comparisons between R^2 and pseudo- R^2 values, as they are not calculated in the same way (Nagelkerke 1991; Kramer 2005), our pseudo- R^2 values suggest that our models have reasonable predictive power, making them roughly comparable to the lower end of the range of predictive ability for previously published models used to estimate Gizzard Shad size. However, our equations do not appear to be as strong as those previously published using TL, FL, SL, or backbone length to predict prey weight ($R^2 = 94$ –99%) or using FL, SL, or backbone length to predict Gizzard Shad TL ($R^2 = 97$ –99%), so these previously published relationships should be favored when digestion is not so advanced as to preclude their use (Knight et al. 1984; Wahl and Stein 1991; Raborn et al. 2002). Nevertheless, gizzards often are intact when the tails and backbones of piscine prey are not, making gizzards a suitable alternative for estimating fish size during situations in which tails and backbones are not intact.

Our 95% CIs indicated good overall precision for mean Gizzard Shad size based on gizzard diameter (i.e., mean values are 95% certain to be within ± 4 –7% of the trend line when predicting weight and within ± 2 –7% of the

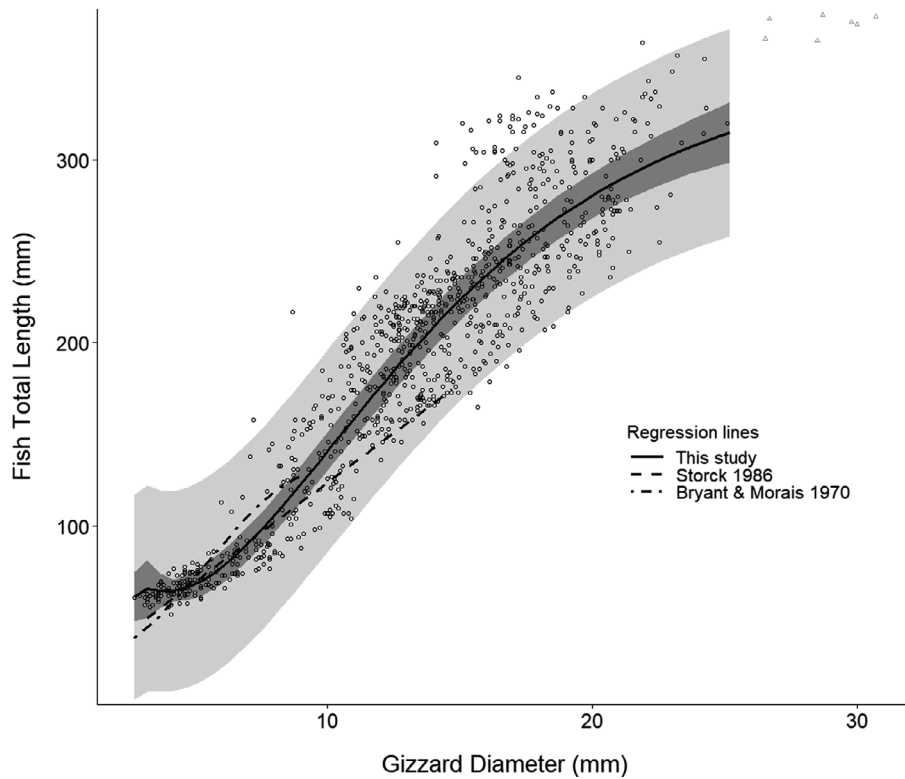


FIGURE 2. Best-fit model (five-parameter Richard's equation, selected from the eight models tested; Table 1) relating maximum gizzard diameter to Gizzard Shad TL. Modeled data are from 936 Gizzard Shad sampled from nine reservoirs in Oklahoma. Circles are data used in the analysis; triangles are data from gizzard diameters larger than 25.1 mm, which did not fit any model well and were omitted prior to final analysis. The dark gray band is the 95% CI of the mean, and the lighter gray band is the 95% prediction interval. The solid line is the trend line from this study; the trend lines from Storck (1986; dashed), and Bryant and Morais (1970; dash-dot) are also displayed for comparison.

trend line for predicting TL over most of the range of gizzard diameters measured). However, the 95% prediction interval (the range encompassing 95% of all observed data) indicated a high degree of individual-specific variation in how well the equation predicted the weight or length of any given Gizzard Shad. This suggests that there could be significant error in the predicted size of any given prey item, but the predictions will still produce mean prey size values that are unbiased (as indicated by the narrow 95% CIs and lack of residual patterns). Therefore, our equations should be useful for diet studies as long as replication is adequate such that mean values converge on true population means. However, practitioners should keep in mind that the actual size of any given prey item could be very different from the value predicted by our models.

Two previous studies have evaluated the gizzard as a structure for estimating Gizzard Shad TL (Bryant and Morais 1970; Storck 1986). Storck (1986) used a linear model to predict the TL of Gizzard Shad from Lake Shelbyville, Illinois, and Bryant and Morais (1970) used a third-order polynomial to model the TL of Gizzard Shad from Beaver Reservoir, Arkansas. Both of their regression models predicted Gizzard Shad TLs similar to those predicted by our

model, which was derived using nine different populations from Oklahoma (Figure 2). This similarity between studies suggests that the allometry between gizzard diameter and TL is likely consistent across Gizzard Shad populations. However, Bryant and Morais (1970) also developed a regression for predicting the length of Threadfin Shad *D. petenense* from gizzard size, and the resulting model made noticeably different predictions than their Gizzard Shad model, suggesting that our regressions would not be suitable for use with this closely related species.

We chose to develop our regression equation using preserved (frozen) Gizzard Shad to be consistent with the common practice of preserving stomach contents for later analysis. Preservation has long been known to cause shrinkage and losses or gains in weight (Garvey and Chipps 2012). However, postmortem shrinkage occurs even in the absence of preservation (Shetter 1936; Morison et al. 2003), indicating that these postpreservation changes likely result from the cessation of osmoregulation and the onset of rigor mortis as much as they result from the use of a preservative. This further suggests that shrinkage of prey items may also occur in predator stomachs once the prey die. Because stomach contents are most often

preserved for later analysis by practitioners, we derived our equations from preserved specimens so that our model predictions would be comparable to length or weight measurements made on lesser-digested prey items in the diet study (i.e., which were also preserved). However, practitioners should be aware that our regressions likely underrepresent live length and could under- or overestimate the live weight of Gizzard Shad. That said, in practical application, preserved and live measurements usually only differ by 1–7% and errors of this magnitude are unlikely to be consequential for the majority of diet analyses. Particular consideration should be given to cases in which predators are measured live and stomach contents are preserved, as this approach would produce a very consistent bias in predator–prey size ratios.

Regressions to predict fish size from partly digested prey are important for conducting diet studies of fishes. Our regressions provide a new option for estimating the size of even heavily digested Gizzard Shad when better correlative metrics (TL, backbone length, etc.) cannot be measured. We recommend the use of TL or backbone length to predict Gizzard Shad weight and the use of backbone length to predict TL when those characteristics can be accurately measured (Wahl and Stein 1991; Raborn et al. 2002) because they more strongly correlate with prey size, but our gizzard diameter regressions provide an option for estimating the size of Gizzard Shad that are too digested to permit the use of other equations.

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