

Allometric growth of invasive lionfish (*Pterois spp*) varies by region in the Western Atlantic

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Abstract

Lionfish (*Pterois volitans* / *miles*) are an invasive species in the Western Atlantic and the Caribbean. Improving management of invasive lionfish populations requires accurate total biomass estimates, which depend on accurate estimates of allometric growth. Sedentary species like lionfish often exhibit high levels of spatial variation in life history characteristics, so we review 17 published length-weight relationships for lionfish taken throughout their invasive range and found substantial regional differences in allometric growth parameters. The spatial pattern we observed is consistent with findings from other studies focusing on genetics or age-at-length. We show that the use of *ex situ* parameters can result in up to a threefold overestimation of total weight, but using parameters from nearby regions reduces this error. These findings can have major implications for management in terms of predicting effects on local ecosystems, evaluating the effectiveness of removal programs, or estimating biomass available for harvest.

Introduction

Lionfish (*Pterois volitans/miles* complex) are an invasive species in the western Atlantic and Caribbean Sea, likely introduced through liberation of aquarium-kept organisms (Betancur-R et al., 2011). They are the first invasive marine vertebrates established along the North Atlantic Caribbean coasts (Schofield, 2009, 2010; Sabido-Itza et al., 2016) and their presence has been labeled as a major marine invasion because they threaten local biodiversity, spread rapidly, and are difficult to manage (Hixon et al., 2016).

A substantial amount of research describes lionfish impacts throughout its invaded range. For example, field

experiments by Albins and Hixon (2008) showed that lionfish establishment led to reduced recruitment of native fishes by nearly 80% over a five week period in Florida. Green et al. (2012) reported that prey fish biomass declined by 65% over two years as lionfish biomass increased along Bahamian coral reefs. A meta-analysis by Peake et al. (2018) showed that invasive lionfish prey on at least 167 different species across the tropical and temperate North Atlantic. Lionfish have also established invasive populations in other habitats such as estuaries, mangroves, hard-bottomed areas, and mesophotic reefs (Barbour et al., 2010; Jud et al., 2011; Muñoz et al., 2011; J.A.B. et al., 2012; Andradi-Brown et al., 2017). Their feeding behavior and high consumption rates can reduce recruitment and population sizes of native reef-fish species, and can further endanger reef fish (Green et al. (2012); Rocha et al. (2015); but see Hackerott et al. (2017)). These trophic impacts can be minimized if local lionfish biomass is controlled by culling (Arias-Gonzalez et al., 2011).

Governments and non-profit organizations have sought to reduce lionfish densities through removal programs and incentivizing its consumption (Chin et al., 2016). In some cases, these have shown to significantly reduce –but not quite eliminate– lionfish abundances at local scales (de Leon et al., 2013; Sandel et al., 2015). Complete eradication of lionfish through fishing is unlikely because of their rapid recovery rates and ongoing recruitment to shallow-water areas from persistent populations in mesophotic ecosystems (Barbour et al., 2011; Andradi-Brown et al., 2017). However, promoting lionfish consumption might create a level of demand capable of incentivizing a stable fishery while controlling shallow-water populations, thus creating alternative livelihoods and avoiding further impacts to local biota.

The feasibility of establishing fisheries through lionfish removal programs has been extensively evaluated through field observations and empirical modeling (Barbour et al., 2011; Morris et al., 2011; de Leon et al., 2013; Johnston and Purkis, 2015; Sandel et al., 2015; Usseglio et al., 2017). Determining the feasibility of such initiatives requires modeling the change in biomass in response to changes in mortality (*i.e.* culling). A common way to model this is via length-structured population models, where fish lengths are converted to weight to calculate total biomass (Barbour et al., 2011; Côté et al., 2014; Andradi-Brown et al., 2017). The allometric length-weight relationship is thus an essential component of these models, but this relationship can vary across regions as a response to biotic and abiotic conditions (Johnson and Swenarton, 2016).

Outcomes of previous studies suggest lionfish are likely to exhibit spatial heterogeneity in the length-weight relationship, which we summarize in two main causes. First, culling programs are effective in reducing local adult populations largely because lionfish exhibit high levels of site fidelity and small home ranges (Fishelson, 1997; Kochzius and Blohm, 2005; Jud and Layman, 2012; Côté et al., 2014). It is known that fish with sedentary behavior are likely to exhibit high levels of spatial variation in important life history

characteristics such as growth or natural mortality rates (Gunderson et al., 2008; Hutchinson, 2008; Wilson et al., 2012; Guan et al., 2013). Second, genetic analysis of lionfish suggests biological differences due to the existence of two genetically distinct invasive subpopulations between the northwest Atlantic and the Caribbean (Betancur-R et al., 2011). Site-specific parameters are necessary to accurately estimate biomass when allometric relationships are spatially variable, and this variability is increasingly important when estimating the potential effectiveness of lionfish culling programs (Barbour et al., 2011; Morris et al., 2011; Côté et al., 2014; Johnston and Purkis, 2015). However, the region-wide differences in allometric growth parameters has remained unexplored for lionfish, despite the large number of site-specific studies reporting the length-weight relationship.

Here, we compare previously published length-weight relationships for lionfish populations in North Carolina, Northern and Southern Gulf of Mexico, the Southern Mexican Caribbean, Bahamas, Little Cayman, Jamaica, Bonaire, Puerto Rico, and Costa Rica (Barbour et al., 2011; Darling et al., 2011; de Leon et al., 2013; Fogg et al., 2013; Dahl and Patterson, 2014; Edwards et al., 2014; Toledo-Hernández, 2014; Sandel et al., 2015; Aguilar-Perera and Quijano-Puerto, 2016; Sabido-Itza et al., 2016; Sabido-Itzá et al., 2016; Chin et al., 2016). We also collected lionfish length and weight data in the central Mexican Caribbean and report the first allometric growth equation for this region. The objective of this paper is to describe the spatial pattern of length-weight relationships of lionfish across the Caribbean and Western Atlantic and to discuss implications of these spatial differences.

Materials and Methods

We reviewed 12 published studies and obtained 17 length-weight relationships for the North Atlantic ($n = 1$), Gulf of Mexico ($n = 7$), and Caribbean ($n = 9$, Table 2, Fig 3). We collected information on sampling methods, sex differentiation, location, and depth ranges from each study when available. Only two studies reported parameters for each gender (Aguilar-Perera and Quijano-Puerto, 2016; Fogg et al., 2013), so we assumed both genders were included in a study if gender was unspecified. Reviewed studies presented information for organisms obtained at depths between 0.5 m and 57 m. Three studies explicitly stated that their organisms were sampled with pole spears (Dahl and Patterson, 2014; Aguilar-Perera and Quijano-Puerto, 2016; Chin et al., 2016; Sabido-Itzá et al., 2016), and five studies mentioned that some of their organisms were obtained with pole spears (or other type of harpoon) but also hand-held nets or fish traps (Barbour et al., 2011; Fogg et al., 2013; Edwards et al., 2014; Toledo-Hernández, 2014; Sandel et al., 2015; Sabido-Itza et al., 2016; Sabido-Itzá et al., 2016), and two studies did not specify how organisms were sampled (Darling et al., 2011;

de Leon et al., 2013). Fogg et al. (2013) use spineless weight in their calculations, so their parameters likely underestimated total weight. Since no spineless to total weight conversions were available, these parameters were taken as reported.

We also collected data from 10 sampling sites along the central Mexican Caribbean coast in 2010 (Table S1). Sampling locations included wall and carpet reefs at depths between 5.7 m and 38.1 m. All observed lionfish ($n = 109$) were collected using hand nets and numbered collection bottles. The use of hand nets prevented any weight loss due to bleeding and allowed better representation of small sizes by eliminating gear selectivity. Organisms were euthanized via pithing and Total Length (TL; mm) and Total Weight (TW; g) were recorded. The weight at length relationship for lionfish in the central Mexican Caribbean was calculated with the allometric growth function:

$$TW = aTL^b \quad (1)$$

Where a is the ponderal index and b is the scaling exponent or allometric parameter. Transforming this equation via base-10 logarithms:

$$\log_{10}(TW) = b \times \log_{10}(TL) + \log_{10}(a) \quad (2)$$

This can be simplified and re-written as:

$$Y = bX + c \quad (3)$$

Where $Y = \log_{10}(TW)$, $X = \log_{10}(TL)$, and $c = \log_{10}(a)$. The coefficients (c and b) were estimated with an Ordinary Least Squares Regression and heteroskedastic-robust standard error correction (Zeileis, 2004). When the $b = 3$, it is said that the organism exhibits a perfect isometric growth, so the b coefficient was tested against the null hypothesis of isometric growth (*i.e.* $H_0 : b = 3$). Coefficients were tested with a two-tailed Student's t , and the significance of the regression was corroborated with an F-test.

Some of the reviewed studies inconsistently defined a as either the ponderal index from Eq. 1 or the y-intercept (c) from Eq. 3. Other studies incorrectly reported parameters as mm-to-g conversions when they were in fact cm-to-g conversions. We standardized each study by converting coefficients and report all parameters as TL(mm) to TW (gr) conversions. Locations where allometric studies have been performed are shown in

Figure 1 and Table 2.

We obtained a total of 18 parameter pairs by combining length-weight parameters extracted from the literature and the additional pair calculated here. We used the central Mexican Caribbean as a case study of how the use of *ex situ* parameters influences the accuracy of weight estimates for lionfish. We estimated TW from the TL observations we collected in the central Mexican Caribbean ($n = 109$) using each of the 18 parameter pairs and divided predicted weights by known observed weights to obtain a simple measure of over- or underestimation. Difference in mean weight ratios across the different parameter pairs were tested with a one-way analysis of variance (ANOVA) and Tukey’s test was used for post-hoc tests. All analyses were performed in R version 3.5.0 (R Core Team, 2018). Raw data and code used in this work are available at dryad.org.

Results

The length-weight relationship for organisms from the central Mexican Caribbean resulted in the coefficient values $a = 3.2056297 \times 10^{-6}$, $b = 3.2347391$ and $c = -5.4940866$ ($R^2 = 0.977$, $F(df = 1; 107) = 6928.67$, $p < 0.001$). The allometric factor (b) was significantly different from $b = 3$ ($t(107) = 6.04$; $p < 0.001$) indicating that lionfish present allometric growth. The length-weight coefficients estimated in this study were within the range identified by studies in other regions (Table 2). Figure 2 shows the relationship between TL and TW for this region, and model fit statistics is presented in Table 1.

There were significant differences in our predicted weights for the central Mexican Caribbean when using the different pairs of parameters ($F(df = 17; 1944) = 61.55$; $p < 0.001$). The lowest weight estimates resulted from using the allometric parameters from Banco Chinchorro in the Caribbean, with mean \pm SD of 40.37 ± 58.74 gr (Sabido-Itzá et al., 2016), and the highest weight estimates came from the Northern Atlantic 73.76 ± 96.11 gr (Barbour et al., 2011). To put this in context, true observed weights were 52.56 ± 76.58 gr. These correspond to predicted-to-observed weights ratios of 0.80 ± 0.19 and 1.76 ± 0.50 (mean \pm SD), respectively.

The calculated ratio of predicted-to-observed weight ranged from 0.36 to 3.51, indicating that *ex situ* parameters can result in major under- and overestimations. Tukey’s post-hoc test suggests that weight ratios for the central Mexican Caribbean were not different from those obtained with parameters from Little Cayman, the Bahamas, and some sites in the Gulf of Mexico (Tukeys HSD $p > 0.05$). Weight estimates using parameters from the Gulf of Mexico and North-Western Atlantic were higher on average than those from the Caribbean (Fig 3). The average (\pm SD) predicted-to-observed weight ratios from these three regions were

1.24 \pm 0.309, 1.76 \pm 0.496, and 1.17 \pm 0.398, respectively. Predicted-to-observed weight ratios are presented in Figure 4. Spineless weight parameters from Fogg et al. (2013) still produced predicted-to-observed weight ratios > 1 .

Discussion

We detected substantial differences in weight-at-length between organisms from the Caribbean, Gulf of Mexico, and North-Western Atlantic. Groupings of predicted-to-observed weight ratios aligned with the spatial distribution of the examined studies, suggesting that these differences are mediated by space. These regional allometric differences mirror similar patterns in age-at-length of lionfish across both their invaded and native regions (Pusack et al., 2016). Variation may be driven by genetics or by organisms' exposure to distinct environmental conditions. For example, Betancur-R et al. (2011) used mitochondrial DNA to demonstrate the existence of two distinct population groups, identified as the "Caribbean group" and "Northern Group", and Fogg et al. (2015) alternatively suggested that age-at-length differences may be climate-driven. Differences in weight-at-length could also reflect differential energy input or usage, or a combination of both. Future research is needed to determine which processes are at work here.

Differences in length-weight relationships have traditionally been highlighted as potential pitfalls to fishery management. For example, Wilson et al. (2012) show that small-scale variations in length-at-age and fishing mortality in other Scorpaeniformes translate to differential landings, effort, and catch per unit effort in the live fish fishery of California, and that these differences must be taken into account in management plans. The lionfish case poses the opposite scenario, where the manager desires to eradicate species. To accurately gauge both the effectiveness of lionfish removal efforts and the resources needed to successfully manage an invasion, we must acknowledge and understand regional biological differences in important variables such as allometric growth parameters.

The results presented here have major implications for management. For example, Edwards et al. (2014) simulated a lionfish culling program under two scenarios, one using length-at-age and length-to-weight parameters from North Carolina and one using parameters from Little Cayman. Their results show that using different parameters caused up to a four-year difference in the time required for the simulated lionfish population to recover to 90% of its initial biomass after removals ceased. Here, we show that using one set of length-weight parameters versus another for a given length can result in up to a threefold overestimation of TW. These spatially-driven differences become especially important when allocating resources for lionfish removal programs, incentivizing lionfish fisheries as a source of alternative livelihoods, or estimating ecosystem

impacts. Research efforts focused on invasive lionfish populations need to use parameters calculated for their region to the extent possible, or at least use reasonable sets of different parameters that provide upper and lower bounds in their results.

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Figures and Tables

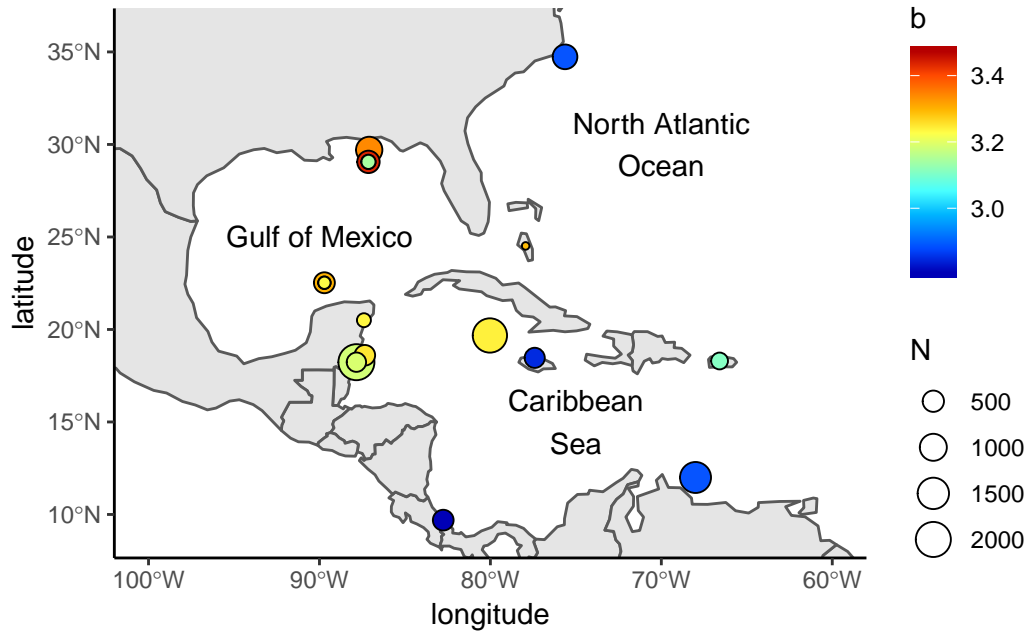


Figure 1: Locations where allometric growth parameters of lionfish (*Pterois spp*) have been reported. Circle sizes indicate sample size from each study, colors indicate the b coefficient from Eq. 1.

Table 1: Coefficients of the linear model fit to Eq 3. Numbers in parentheses represent heteroskedastic-robust standard errors.

	$\log_{10}(TW)$
c	$-5.494 (0.083)^{***}$
b	$3.235 (0.039)^{***}$
F Statistic	6928.67 ^{***} (df = 1; 107)
Observations	109
Adjusted R ²	0.976
Residual Std. Error	0.096 (df = 107)
Note:	*p<0.1; **p<0.05; ***p<0.01

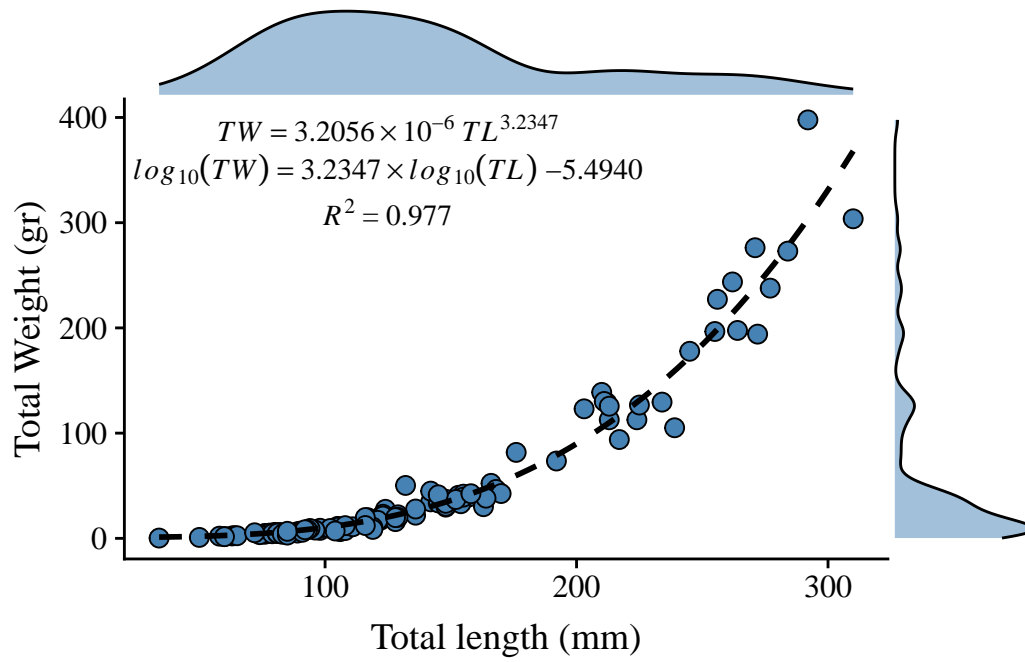


Figure 2: Length-weight relationship for 109 lionfish sampled in the central Mexican Caribbean. Points indicate samples, dashed black line indicates curve of best fit, marginal plots represent the density distribution of each variable.

Table 2: Summary of 18 allometric growth parameters available for lionfish in the invaded range from peer-reviewed literature and this study. All parameters have been adjusted to convert from millimeters to grams. n = Sample size, Sex specifies whether data was presented for Females (F), Males (M), or both genders combined (B), a = scaling parameter for Eq. 1 (presented in $\times 10^{-5}$), c = y-intercept for Eq. 3, b = exponent or slope for Eq. 1 or Eq. 3, respectively. The R^2 column indicates reported model fit.

Region	Sex	n	a	b	c	R^2	Reference
Caribbean	B	458	3.6	2.81	-4.44	-	Sandel et al., 2015
Caribbean	B	419	2.8	2.85	-4.56	0.8715	Chin et al., 2016
Caribbean	B	1450	2.3	2.89	-4.64	0.96	de Leon et al., 2013
Caribbean	B	1887	0.3	3.24	-5.52	0.97	Edwards et al., 2014
Caribbean	B	-	0.25	3.29	-5.60	-	Darling et al., 2011
Caribbean	B	2143	0.52	3.18	-5.28	0.9907	Sabido-Itza et al., 2016
Caribbean	B	227	0.8	3.11	-5.10	0.958	Toledo-Hernández et al., 2014
Caribbean	B	449	0.23	3.25	-5.64	0.97	Sabido-Itza et al., 2016b
Caribbean	B	368	0.32	3.19	-5.50	0.98	Sabido-Itza et al., 2016b
Caribbean	B	109	0.32	3.23	-5.49	0.9766	This study
GoM	B	934	0.21	3.34	-5.68	0.98	Dahl & Patterson, 2014
GoM	B	472	0.29	3.30	-5.54	0.95	Aguilar-Perera & Quijano-Puerto, 2016
GoM	F	67	0.12	3.47	-5.93	0.95	Aguilar-Perera & Quijano-Puerto, 2016
GoM	M	59	0.42	3.23	-5.38	0.95	Aguilar-Perera & Quijano-Puerto, 2016
GoM	B	582	0.14	3.43	-5.86	0.99	Fogg et al., 2013
GoM	M	119	0.27	3.31	-5.57	0.97	Fogg et al., 2013
GoM	F	115	0.68	3.14	-5.17	0.94	Fogg et al., 2013
North Atlantic	B	774	2.9	2.89	-4.54	-	Barbour et al., 2011

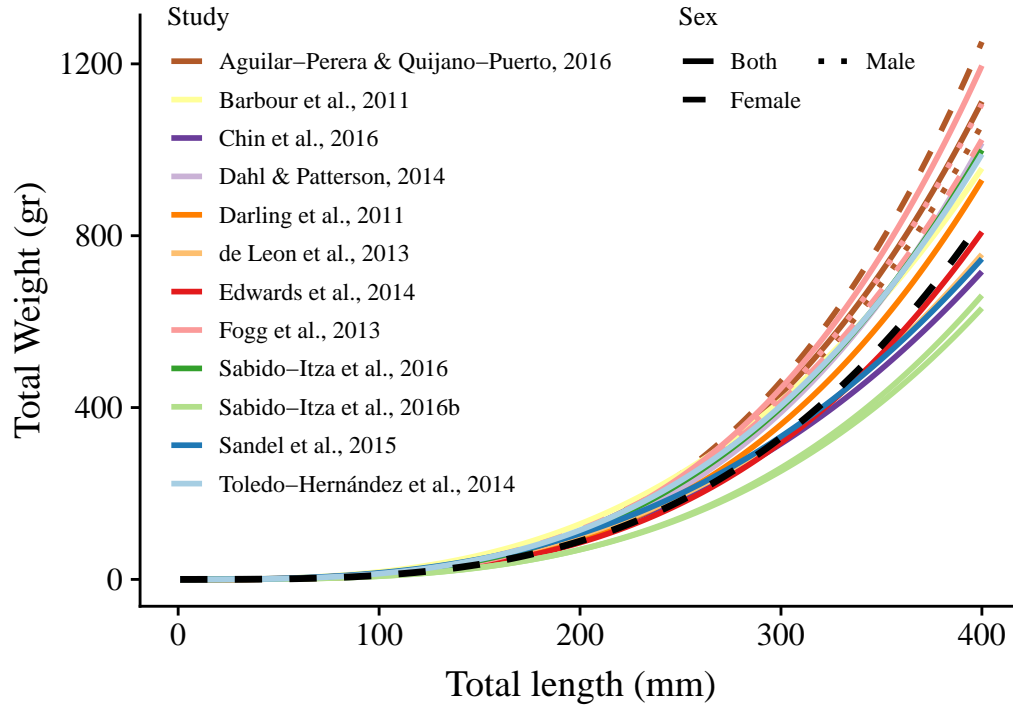


Figure 3: Length-weight relationships ($n = 18$) for 12 studies and this study. Colors indicate studies from which the parameters were extracted. Dotted, dashed and solid lines show models for males, females, and combined sexes, respectively. The dashed black line represents the relationship estimated in this study.

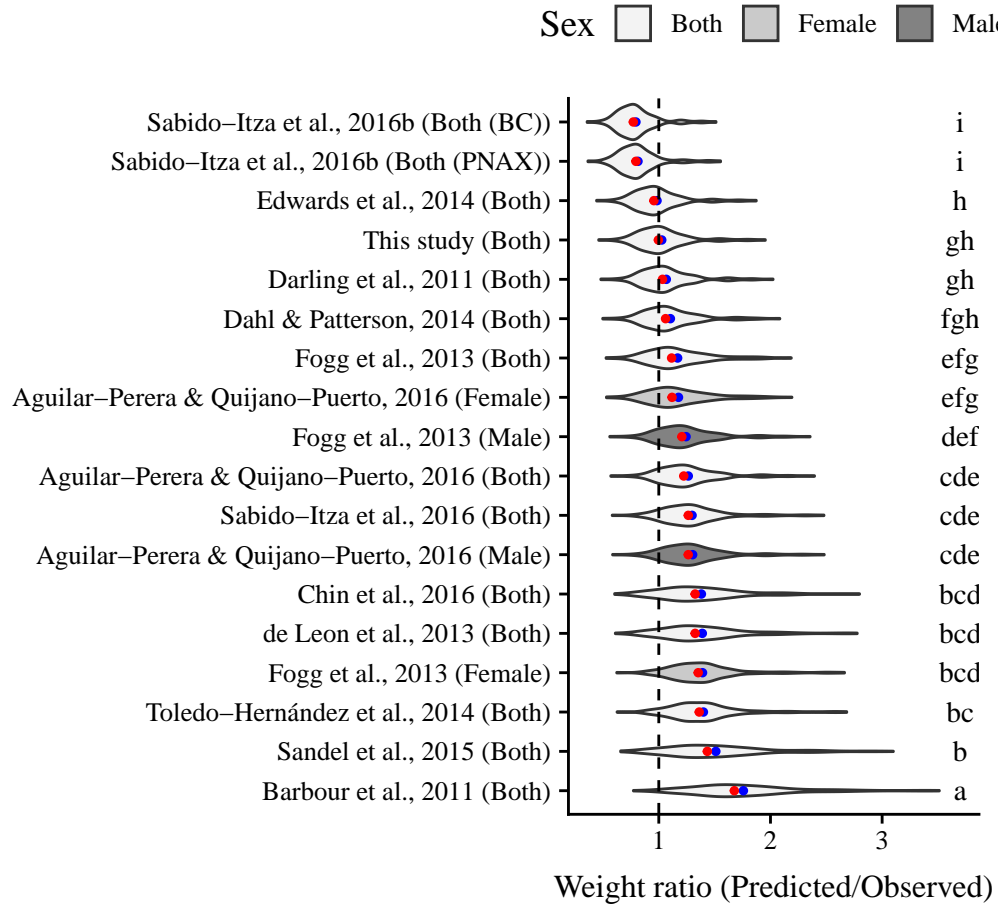


Figure 4: Violin plot of predicted-to-observed weight ratios for 18 pairs of allometric parameters. Red and blue circles indicate median and mean values, respectively. Like letters indicate values that do not differ significantly.