Biometry of the invasive lionfish (*Pterois volitans*) in Playa del Carmen, Mexico and a review of length - weight parameters across the invasion range

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Title of the contribution: Biometry of the invasive lionfish (*Pterois volitans*) in Playa del Carmen, Mexico and a review of length - weight parameters across the invasion range

Abstract

300 words

Key words

lionfish, biometry, length-weight relationship, Mexico

Resumen

300 palabras

Palabras clave

pez león, biometría, relación lopngitud-peso, México

Introduction

At least 84% of the marine eco-regions have reported the presence of an invasive species (Molnar, Gamboa, Revenga, & Spalding, 2008). The presence of invasive alien species represents a major threat to local biodiversity and the economic activities that depend on it, like tourism or fisheries (Bax, Williamson, Aguero, Gonzalez, & Geeves, 2003). By 2005, the economic cost of invasive species to the United States was estimated at $120 billion per year and nearly 42% of species that have been included in the Endangered or Threatened species list have been labeled as such due to presence of invasive species (Pimentel, Zuniga, & Morrison, 2005). Invasive species may threaten native species through competition (Davis, 2003) or predation. This highlightes the importance of understanding, managing, and preventing ecological invasions.

Lionfish (*Pterois volitans - miles* complex) are an invasive species in the North-Western Atlantic and the Caribbean likely introduced through libreation of aquarium-kept organisms (Betancur-R et al., 2011). They are the first marine vertebrates to establish in North Atlantic (Schofield, 2009: Schofield (2010)) and Caribbean coasts. Lionfish have been recorded in coral reefs (Aguilar-Perera & Tuz-Sulub, 2010), but also in other habitats like estuaries (Jud, Layman, Lee, & Arrington, 2011), mangroves (A. Barbour, Montgomery, Adamson, D?az-Ferguson, & Silliman, 2010) and hard-bottom reefs (Muñoz, Currin, & Whitfield, 2011). Their presence in these waters has been labeled as a major marine invasion due to its threat to local biodiversity, the veolocity of its invasion, and its difficulty of management (Hixon, Green, Albins, Akins, & Morris, 2016).

As ways to reduce the abundance of this invasive species local authorities have promoted removal programs incentivized consumption of this invasive species (Chin, Aiken, & Buddo, 2016). Lionfish removals have shown to significantly reduce -but not quite eliminate- lionfish abundances at local scales (Sandel, Martinez-Fernández, Wangpraseurt, & Sierra, 2015, Chin et al. (2016), de Leon et al. (2013)). While complete erradication through fishing effort is unlikely to be a solution due to the rapid recovery rates exhibited by the species (A. B. Barbour, Allen, Frazer, & Sherman, 2011), further incentivizing its consumption might create a market demand big enough to promote a fishery (Chin et al., 2016).

A significant amount of research has been done on lionfish feeding ecology in North Carolina (Muñoz et al., 2011), the Bahamas (Cote, Green, Morris Jr, Akins, & Steinke, 2013; J. A. Morris & Akins, 2009), Northern Gulf of Mexico (Dahl & Patterson, 2014), Mexican Caribbean (Valdez-Moreno, Quintal-Lizama, Gómez-Lozano, & García-Rivas, 2012; Villaseñor-Derbez & Herrera-Pérez, 2014), and Costa Rica (Sandel et al., 2015). It has been identified that lionfish can reduce recruitment (Albins & Hixon, 2008) and population sizes (Green, Akins, Maljković, & Côté, 2012) of native reef-fish species, and further the endangerement of critically endangered reef fish (L. A. Rocha, Rocha, Baldwin, Weigt, & McField, 2015). This information has been useful in predicting the trophic impacts of lionfish (Arias-Gonzalez, Gonzalez-Gandara, Luis Cabrera, & Christensen, 2011). Significant efforts have also been made to understand the possible impacts of the invasion by keeping track of the invasion range through time (Schofield, 2009, 2010) and predicting invasion ranges under climate change scenarios (Grieve, Curchitser, & Rykaczewski (2016)).

Biomass is a standard indicator used to measure the state or size of a population. Biomass has been used in lionfish research to convert individual fish length observations into fish weight. In order to do this, researchers must find growth parameters thad describe the growth of their species for a particular region or location. Having precision of these parameters is important, because small changes in any of them can result in important over- or underestimation of biomass levels. This becomes particularly important when research involves, for example, identifying the total biomass available for harvest by fishers -as invasion management programs- or the efficacy of lionfish removals.

The objectives of this study include providing site-specific weight-at-length parameters for the invasive lionfish in the Mexican Caribbean region. At the same time, we highlight the importance of using site-specific parameters by estimating biomass with parameters from other regions across the invasion range and comparing them to observed biomasses. Finally, we summarize other weight-at-length studies presented, making them readily accessible for future research.

Materials and Methods

Area of study

The present study took place off the coasts of Playa del Carmen, in the coasts of the Mexican Caribbean. The region represents the northernmost section of the Mesoamerican reef, which extends from coast of Cancun south to Honduras (**reference**). Coral reefs and mangroves are important habitats distributed along the cost, and represent important sources of income in terms of extractive (*e.g.* recreational fishing) and non-extractive (*e.g.* SCUBA diving) activities related to tourism (**reference**), the main source of income to the local economy.

Coral reefs in the region are characterized by X, Y, Z. Descripcion general de los arrecifes.

Fish sampling

The present study used samples obtained by Villaseñor-Derbez & Herrera-Pérez (2014) for stomach content analysis between May and August of 2010. A total of 33 SCUBA immersions were performed in 10 sampling sites along 14 Km of coast between Puerto Aventuras and Akumal (Fig. 1, Table 1). Sampling locations included wall and carpet reefs at depths between 5.7 m and 38.1 m. All observed organisms (n = 109) were collected using hand nets -to avoid weight loss due to bleeding- and numbered collection bottles. Information on depth and other comments were recorded in an underwater slide. Depth was recorded by dive gauges held by divers as safety procedures during the collections. Samples were frozen within 30 minutes of completing the dive and stored for posterior analysis in the lab. For every organism, Total Length (TL; mm) and Total Weight (TW; gr) were recorded in the lab.

Data analysis

The weight at length relationship between the observed variables was calculated with the allometric growth function:

$$TW = aTL^b \tag{1}$$

Where TW is the Total Weight (gr), TL is the observed Total Length (mm), a is the ponderal index and b is the scaling exponent or allometric parameter. When $b = 3$, it is said that the organism exhibits a perfect isometric growth. The dependent and independent variables were transformed via base-10 logarithms so that the equation is then:

$$log_{10}(TW) = blog_{10}TL + log10(a) \tag{2}$$

To simplify this equation, we can re-write it as:

$$Y = mX + c \tag{3}$$

Where $Y = log_{10}(TW)$, $X = log_{10}(TL)$, $m = b$, and $c = log_{10}(a)$. The coefficients (c and b) were estimated with an Ordinary Least Square Regression and heteroskedastic-robust standard errors. Both coefficients were tested agains the null hypothesis of no change (*i.e.* $h_0 : c = 0$ and $h_0 : b = 0$). Additionally, the allometric parameter was tested against the null hypothesis of isometric growth ($H_0 : b = 3$). Coefficient testing was made with a two-tailed Student's t-test. The significance of the regression was corroborated with an F-test.

Other growth parameters were extracted from published research from North Carolina (A. B. Barbour et al., 2011), Northern (Fogg et al., 2013) and Southern (Aguilar-Perera & Quijano-Puerto, 2016) Gulf of Mexico, the Southern Mexican Caribbean (Sabido-Itza, Medina-Quej, De Jesus-Navarrete, Gomez-Poot, & Garcia-Rivas, 2016), Little Cayman (Edwards, Frazer, & Jacoby, 2014), Jamaica (Chin et al., 2016), Bonaire (de Leon et al., 2013) and Costa Rica (Sandel et al., 2015). Additionally, parameters from Fishbase (Froese & Pauly, 2016) were also included in this study. When available, information on sampling methods, gender differentiation, location, and depth ranges of each study was retreived. Whenever gender was not specified, it was assumed that the results were presented for both genders pooled together. During this review process, it was noticed that some papers indistinctly use a to report either the ponderal index in **eq. 1** or the y-intercept (c) in **eq. 2**, which might sometimes be overlooked. Furthermore, some studies report their parameters as mm-to-gr conversions, but a rapid evaluation of such parameters indicates that they were estimated as cm-to-gr conversions. Here, both parameters (a and c) are reported for the present findings and, when ever required, values from other studies are converted for consistency. All coefficients are reported as mm to gr conversions.

Mean observed biomass was calculated as the average Total Weight of all observed organisms. Expected biomass for each organism was calculated with the growth parameteres estimated in this study, as well as those retreived from additional literature. Then, mean expected biomass was calculated for each study. All expected biomass values were divided by the observed biomass to obtain a ratio that allowed rapid identification of over- or underestimation with respect to the observed biomass in this study. Therefore, values lower than 1 indicate that the parameters used underestimate the biomass. On the other side, values larger than 1 indicate that the parameteres used overestimate biomass. Median and mean expected to observed biomass ratios were calculated across all sites for each study.

All hypothesis testing was performed with a confidence level of $\alpha = 0.01$ and performed in

R version 3.4.0 (R Core Team, 2017). Data wrangling was performed with the tidyverse package (Wickham, 2017). Maps were created with a mix of functions from the sp (Pebesma & Bivand, 2005), rgdal (R. Bivand, Keitt, & Rowlingson, 2017), tmap (Tennekes, 2017a), and tmaptools (Tennekes, 2017b) packages. Correction for heteroskedastic-robust standard errors was done with the sandwich (Zeileis, 2004) and lmtest (Zeileis & Hothorn, 2002) packages. Models were manipulated with with the broom package (Robinson, 2017). Stargazer (Hlavac, 2015) was used to produce the tables, and refmanager (McLean, 2014) was used to keep track of citations. The manuscript was written in rmarkdown (Allaire et al., 2017) and processed with the knitr package (Xie, 2017).

Results

A summary of Total Lengths and Total Weights of the the sampled organisms (n = 109) is presented in Table 2. The smallest organism (TL = 34.00 mm) was also the lightest organism (TW = 0.30 gr). However, the largest organism (TL = 310.00 mm) was not the heaviest (TW = 303.70 gr), and the heaviest organism (TW = 397.70 gr) was 292.00 mm in total length. Kernell density plots (Fig. 2) show the distribution for TL and TW. Both measures were positively skewed, with skewness of 0.85 for TL and 2.19 for TW.

Length-weight relationship

The model adjusted to eq. 3 estimated the coefficient values at $m = 3.2347391$ and $c = -5.4940866$. The intercept and slope were significantly different from zero ($t(107) = -66.17; p < 0.01$ and $t(107) = 83.24; p < 0.01$, respectively), rejecting the null hypothesis of no change. Additionally, the allometric factor was significantly different from zero ($t(107) = 6.04; p < 0.01$). More information on model fit and confidence intervals for the estimated coefficients are presented in Table 3. The relationship between Total Length and

Total Weight is presented in Figure 3.

Comparison of allometric parameters

From the eight peer-reviewd studies including information on growth parameters for *P. volitans* and FishBase (Froese & Pauly, 2016), 13 parameters were identified. Two studies (Aguilar-Perera & Quijano-Puerto, 2016; Fogg et al., 2013) reported gender-level and pooled parameters, while the rest of the studies always presented pooled results. The smallest coefficient of determination was presented by Chin et al. (2016) with $R^2 = 0.8715$, while Sabido-Itza et al. (2016) reported the highest value at $R^2 = 0.8715$. These studies presented information for organisms obtained at depths between 0.5 and 57 meters. Two studies (Aguilar-Perera & Quijano-Puerto, 2016; Chin et al., 2016) explicitly stated that their organisms were sampled with pole spears. Five studies (A. B. Barbour et al., 2011; Edwards et al., 2014; Fogg et al., 2013; Sabido-Itza et al., 2016; Sandel et al., 2015) mentioned that some of their organisms were obtained with pole spears (or other type of harpoon). A single study (de Leon et al., 2013) did not specify how samples were obtained.

Parameters from models fit to males or females exclusively tend to have a higher steapness (*i.e.* higher allometric parameter), with mean $\pm$ standard deviation values of $b = 3.27 \pm 0.06$ and $b = 3.31 \pm 0.23$, compared to parameters from models for pooled genders with a mean $\pm$ standard deviation value of $b = 3.09 \pm 0.22$. In the case of the ponderal index (a) and its log_{10} transformed parameter (c), values were higher for parameters for pooled genders. The trends in a, c, and b indicate that some models will tend to estimate Total Weights differently. Figure 4 shows the predicted weights for organisms within the size range of these study using the 14 parameters previously described.

From all allometric parameters reviewed, those of Edwards et al. (2014) slightly underestimated the observed biomass, with median (0.96) and mean (0.98) bellow one. There is no significance in comparing the parameters estimated in this study since, by definition, they are the pair of parameters for which residual sum of squares was minimized with values of median =1.00 and mean (1.03). For all the other studies, the 95% confidence interval fell further away from a value of 1, indicating overestimation. Predicted to observed biomass ratios are presented in Figure 5.

Discussion and Conclusions

Wider range sizes

Model fit and this model

No spear doesnt seem to be a determinant factor in weight, but spear doesnt allow catching small organisms. Not using spear poles allows us to have a full sample of fish with a wider range of sizes and weights, ideal for visual census. Also, there is no loss in body mass due to bleeding.

Gender-level overestimates and is steaper because it lacks small organisms to pull the curve

Aknowledgements

Tables

Location table

Table 1: Coordinates, minimum, maximum and mean depth (m), and number of samples for each location. n = sample size.

Location	Lat.	Long.	Min. Depth	Max. Depth	Mean Depth	n
Canones	20.477	-87.233	15.0	31.2	21.6	11
Castillo	20.496	-87.220	12.5	30.5	27.5	18
Cuevitas	20.478	-87.244	7.4	12.8	11.2	4
Islas	20.490	-87.228	14.0	19.4	16.7	10
Paamul	20.513	-87.192	9.9	22.7	15.5	31
Paraiso	20.484	-87.226	9.4	38.1	17.7	16
Pared	20.502	-87.212	12.1	21.0	16.3	12
Pedregal	20.507	-87.204	14.4	14.9	14.7	3
Santos	20.493	-87.222	5.7	26.6	16.2	2
Tzimin-Ha	20.393	-87.307	21.2	24.6	22.9	2
Total			5.7	38.1	18.6	109

Summary table

Table 2: Summary statistics of Length and Weight of sampled organisms.

Statistic	N	Mean	St. Dev.	Min	Max
Length	109	140.22	62.41	34	310
Weight	109	52.56	76.58	0.30	397.70

Regression table

Table 3:

	Dependent variable:
	log10(Weight)
Constant	−5.494 (−5.657, −5.331)***
log10(Length)	3.235 (3.159, 3.311)***
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

Review table

Table 4: Allometric growth parameters for eight published papers, Fishbase (Froese and Pauly 2016), and this study. All parameters have been adjusted to convert from millimeters to grams. n = Sample size, a = scaling parameter for eq. 1, c = y-intercept for eq. 3, b = exponent or slope for eq. 1 or eq. 2, respectively.

Reference	n	a	c	b	r2	Gender	minD	ma
Aguilar-Perera & Quijano-Puerto (2016)	472	3.0e-06	-5.5400	3.3000	0.9500	Both	5.0	[illegible]
Aguilar-Perera & Quijano-Puerto (2016)	67	1.0e-06	-5.9300	3.4700	0.9500	F	5.0	[illegible]
Aguilar-Perera & Quijano-Puerto (2016)	59	4.0e-06	-5.3800	3.2300	0.9500	M	5.0	[illegible]
Sandel et al. (2015)	458	3.6e-05	-4.4400	2.8100	NA	Both	NA	
Chin et al. (2016)	419	2.8e-05	-4.5600	2.8500	0.8715	Both	18.3	
A. B. Barbour et al. (2011)	774	2.9e-05	-4.5391	2.8900	NA	Both	27.0	[illegible]
de Leon et al. (2013)	1450	2.3e-05	-4.6411	2.8900	0.9600	Both	NA	
Fogg et al. (2013)	582	1.0e-06	-5.8600	3.4349	0.9900	Both	NA	
Fogg et al. (2013)	119	3.0e-06	-5.5700	3.3100	0.9700	M	NA	
Fogg et al. (2013)	115	7.0e-06	-5.1700	3.1437	0.9400	F	NA	
Edwards et al. (2014)	1887	3.0e-06	-5.5229	3.2400	0.9700	Both	15.0	[illegible]
Sabido-Itza et al. (2016)	2143	5.0e-06	-5.2828	3.1832	0.9907	Both	0.5	[illegible]
Froese & Pauly (2016)	NA	9.0e-06	-5.0293	3.0900	NA	Both	NA	
This study	109	3.0e-06	-5.4941	3.2347	0.9766	Both	5.7	[illegible]

Figures

Map

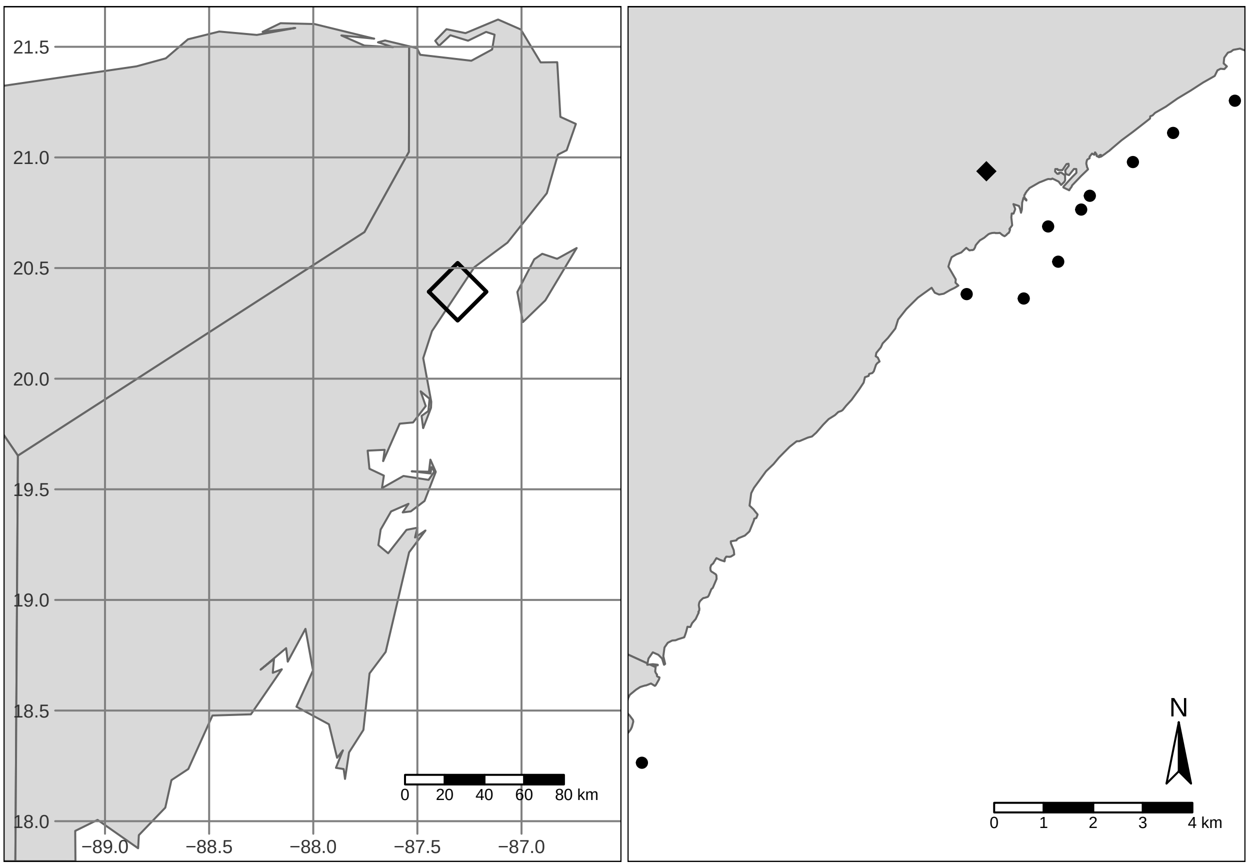

Figure 1: Map of the study area. The black inset on the left indicates the location where study sites are distributed. On the right, circular markers indicate sampling sites and the black romboid indicates location of Puerto Aventuras.

Histograms

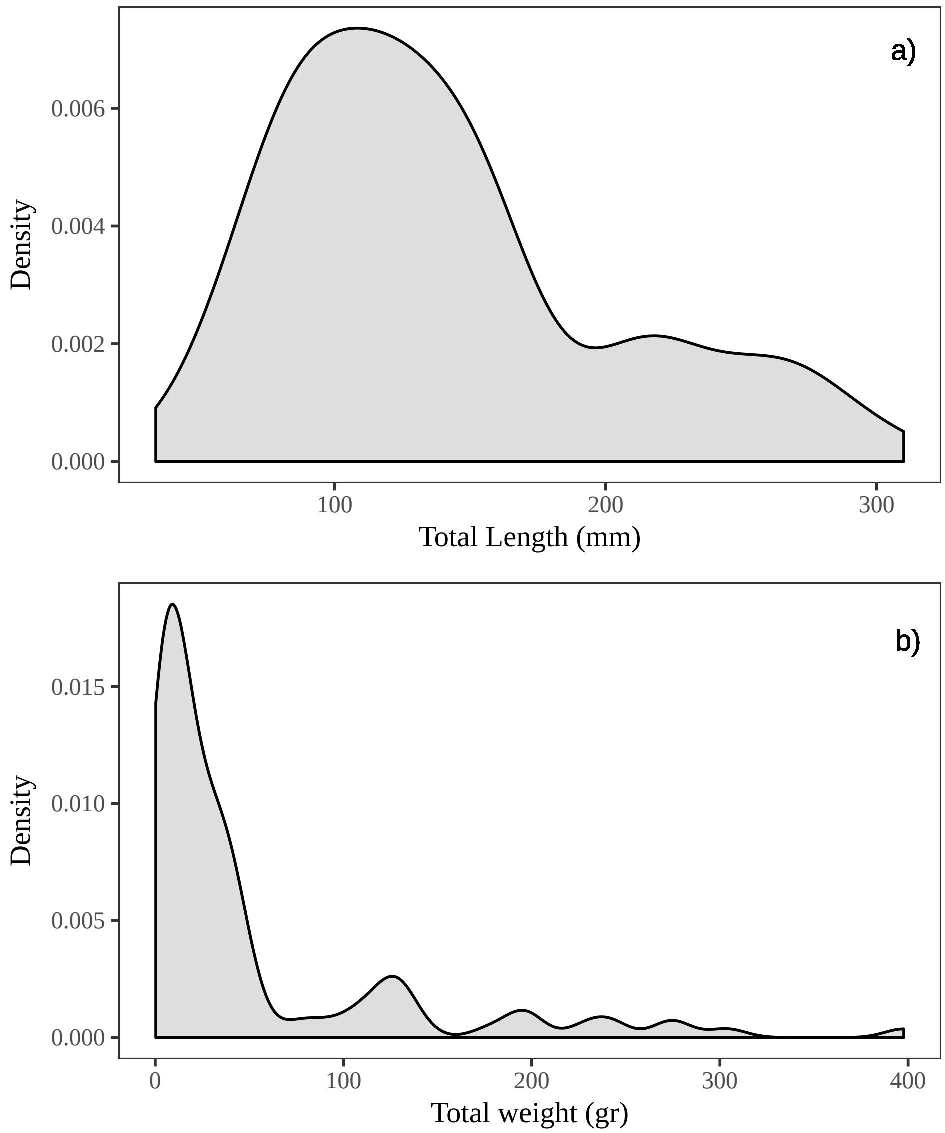

Figure 2: Kernell density plots for a) Total length (mm) and b) Total weight (gr) for 109 lionfish sampled off the coast of Puerto Aventuras, Mexico.

Scatter plot

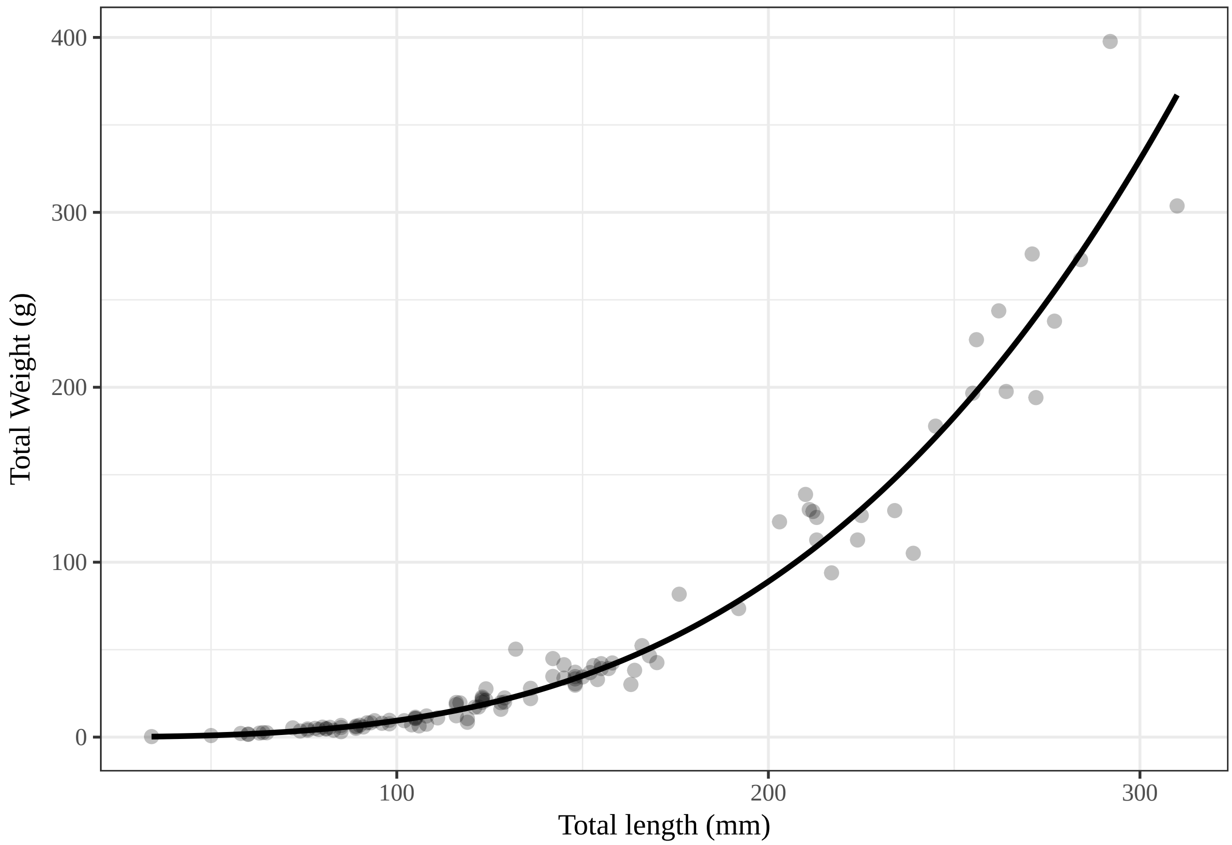

Figure 3: Weight-at-length relationship for 109 lionfish sampled off the coast of Puerto Aventuras, Mexico. Points indicate samples, solid line indicates curve of best fit.

Review plots

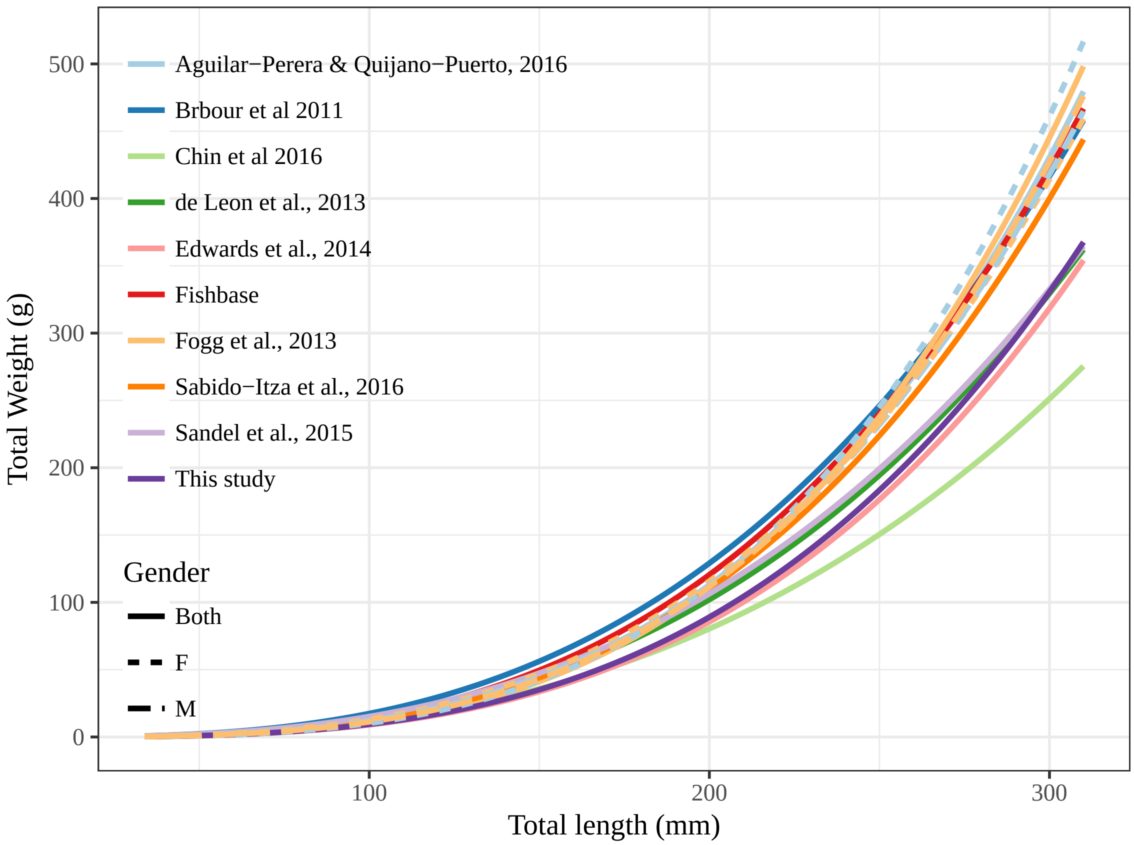

Figure 4: Weight-at-length relationships (n = 14) for eight studies, this study, and FishBase parameters. Colors indicate studies from which the parameters were extracted. Solid lines indicate that the fit was performed for males and females pooled together. Dotted lines indicate that the regression was performed on females, and dashed lines indicate it was performed for males.

221 # Predictions plot

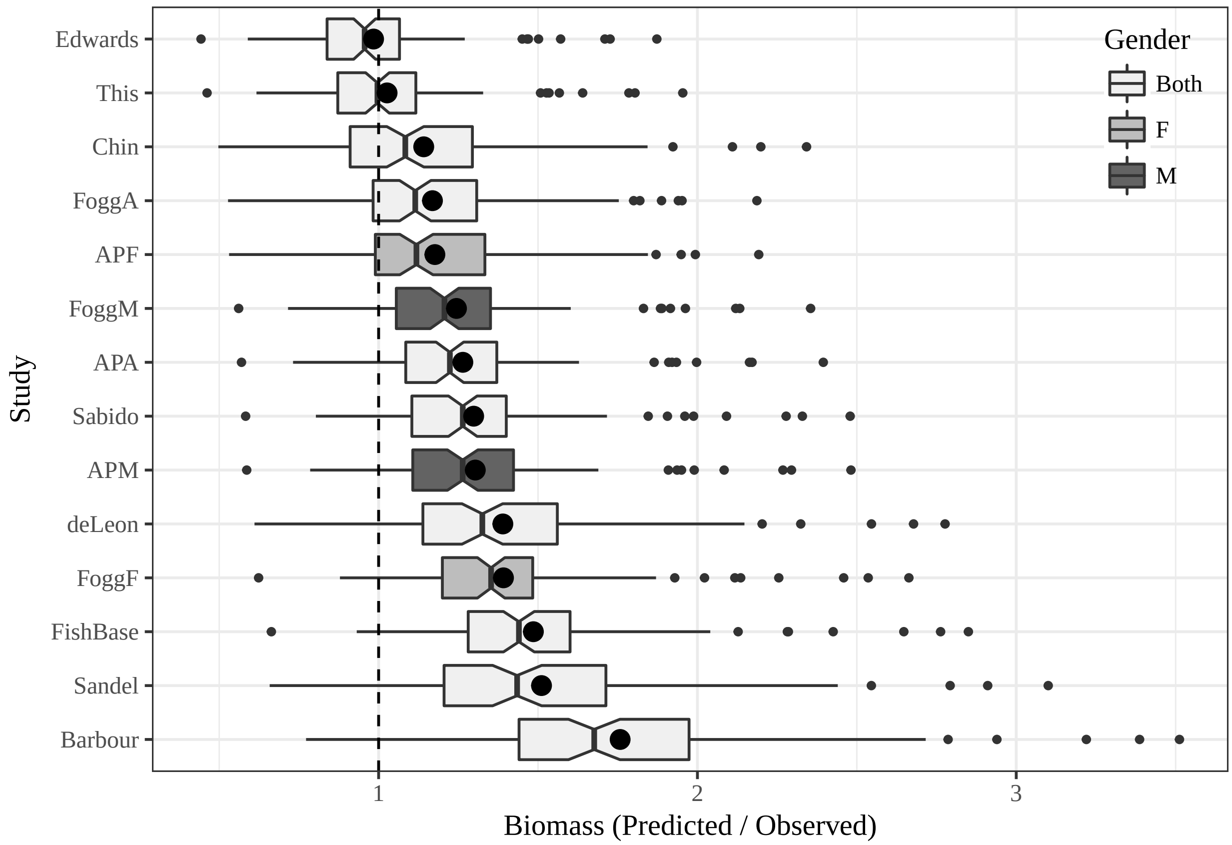

Figure 5: . Box and whiskers plot showing the distribution of predicted to observed Total Weight ratios for 14 pairs of allometric parameters. Lines indicate median values, circles indicate mean values, notches represent 95% confidence intervals arround the median, lower and upper hinges correspond to the first and third quartiles, whiskers extend to the largest and lowes values within 1.5 inter-quartile range of the hinge, small points represent outliers further away than the whiskers.

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