Biometry of the invasive lionfish (*Pterois volitans*) in Playa del Carmen, Mexico and a review of allometric growth 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 et al. 2008). These represents a major threat to local biodiversity and the economic activities that depend on it, like tourism or fisheries (Bax et al. 2003). Invasive species may also threaten native species through competition (Davis 2003) or predation. 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, and Morrison 2005). 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 (Sabido-Itza et al. 2016). Lionfish have been widely reported in coral reefs (Aguilar-Perera and Tuz-Sulub 2010), but also in other habitats such as estuaries (Jud et al. 2011), mangroves (Barbour et al. 2010), areas with hard-bottoms (Muñoz, Currin, and Whitfield 2011), and mesophotic reefs (Andradi-Brown et al. 2017). Due to its threat to local biodiversity, the speed of their spread, and its difficulty of management, their presence in these waters has been labeled as a major marine invasion (Hixon et al. 2016).

A significant amount of research has been done to describe lionfish feeding ecology in North Carolina (Muñoz, Currin, and Whitfield 2011), the Bahamas (Morris and Akins 2009; Cote et al. 2013), Northern Gulf of Mexico (Dahl and Patterson 2014), Mexican Caribbean (Valdez-Moreno et al. 2012; Villaseñor-Derbez and Herrera-Pérez 2014), and Costa Rica (Sandel et al. 2015). Their feeding behaviour and high consumption rates can reduce recruitment (Albins and Hixon 2008) and population sizes (Green et al. 2012) of native reef-fish species, and further the endangerement of critically endangered reef fish (Rocha et al. 2015). Major efforts have also been made to understand the possible impacts of the invasion by keeping track of its range through time (Schofield 2009; Schofield 2010) and predicting invasion ranges under climate change scenarios (Grieve, Curchitser, and Rykaczewski (2016)). By combining these information, researchers have been ableto predict the trophic impacts of lionfish (Arias-Gonzalez et al. 2011), which can then be translated into ecosystem-level impacts.

Seeking to reduce the abundance of this invasive species, local authorities have promoted removal programs ands incentivized its consumption (Chin, Aiken, and Buddo 2016). Lionfish removals have shown to significantly reduce -but not quite eliminate- lionfish abundances at local scales (Sandel et al. 2015, Chin, Aiken, and Buddo (2016), de Leon et al. (2013)). The rapid recovery rates exhibited by lionfish make of complete erradication through fishing effort an unlikely solution (Barbour et al. 2011). However, further incentivizing its consumption might create a demand big enough to promote and sustain a stable fishery (Chin, Aiken, and Buddo 2016), which can reduce local abundances and control -not erradicate- the invasion.

Research focused on erradication and management effectivenes must be based on sound biological information, highlighting the importance of both fields. Management effectiveness often identified the gains associated to the invested effort, like biomass extracted per dollar. Among fish, biomass is often used as a standard measure of the state or size of a population. By deffinition, biomass is the sum of the weight of all organisms. In some cases, a fish's weight is directly measured, in others, weight can be calculated from length data. In order to do this, researchers must find allometric parameters that describe the weight-at-length for their species of interest at a particular region. Having precision of these parameters is important, because small changes in any of them can result in over- or underestimation of an organisms weight, and therefore total biomass. This becomes particularly important when research involves, for example, identifying the total biomass available for harvest by fishers

(Chin, Aiken, and Buddo 2016) or the efficacy of lionfish removals (Barbour et al. 2011).

Here, I provide site-specific allometric growth parameters for the invasive lionfish in the central Mexican Caribbean region, where no studies have been published. At the same time, I 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 biomass. Finally, I provide a review of other weight-at-length studies -making them readily accessible for future research- and provide a set of guidelines to standardize the way in which allometric parameters should be reported to facilitate their use.

Materials and Methods

Area of study

The study took place off the coasts of Playa del Carmen, in the Mexican Caribbean (**Fig. 1**). The region represents the northernmost section of the Mesoamerican Barrier Reef System (**???**). Coral reefs and mangroves are localy important habitats that represent important sources of income in terms of extractive (*e.g.* recreational fishing) and non-extractive (*e.g.* SCUBA diving) activities related to tourism, the main source of income to the local economy (Murray 2007).

In the region, reef profile has been described by (**???**), where the reef lagoon extends about 500 m from the coast, until the reef crest is reached. The reef becomes deeper, leading to the reef front often found at 700 m from the coastline end extends for an additional 300 m. At approximately 1000 m away from shore and 30 - 40 m depth, the reef leads to a drop-off. Along a perpendicular profile to the coast, bands of reef are interrupted by sand patches at 8 - 12 m deep and 16-18 m deep. Along the coast, these reefs have been reported to be under significant antrhopogenic pressure, likely causing a shift in structure and function (**???**).

Fish sampling

Organisms sampled by Villaseñor-Derbez and Herrera-Pérez (2014) for stomach content analysis between May and August of 2010 were used in this work. 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 (Barbour et al. 2011), Northern (Fogg et al. 2013) and Southern (Aguilar-Perera and Quijano-Puerto 2016) Gulf of Mexico, the Southern Mexican Caribbean (Sabido-Itza et al. 2016), Little Cayman (Edwards, Frazer, and Jacoby 2014), Jamaica (Chin, Aiken, and Buddo 2016), Bonaire (de Leon et al. 2013) and Costa Rica (Sandel et al. 2015). Additionally, parameters from Fishbase (Froese and 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 $\alpha = 0.01$ 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 and Bivand 2005), rgdal (Bivand, Keitt, and Rowlingson 2017), tmap (Tennekes 2017a), and tmaptools (Tennekes 2017b) packages. Callculation of heteroskedastic-robust standard errors was done with the sandwich (Zeileis 2004) and lmtest (Zeileis and 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). Raw data and code used in this work is available at github.com/jcvdav/lionfish_biometry.

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 and Pauly 2016), 13 parameters were identified. Two studies (Aguilar-Perera and 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, Aiken, and Buddo (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 and Quijano-Puerto 2016; Chin, Aiken, and Buddo 2016) explicitly stated that their organisms were sampled with pole spears. Five studies (Sandel et al. 2015; Barbour et al. 2011; Fogg et al. 2013; Edwards, Frazer, and Jacoby 2014; Sabido-Itza et al. 2016) 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, Frazer, and Jacoby (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

Here, I provide site-specific allometric growth parameters for the invasive lionfish in the central Mexican Caribbean region, where no studies have been published.

Other studies have provided allometric growth parameters of lionfish in Mexican waters, specifically for the Alacranes Reef, in the Gulf of Mexico (**???**), and further south in the Caribbean for the Xcalak National Park (Sabido-Itza et al. 2016), but no information for the central region of the Mexican Caribbean coast had been provided. Furthermore by using hand nets instead of spears, we are able to sample a wider range of sizes, extending the lower length classes to smaller organisms often not sampled with spears. Thus, this study is the first to provide allometric growth parameters for lionfish in the central region of the Mexican Caribbean and includes a wider range of total lengths, allowing us to calculate -with certainty- a wider range of weights.

The parameters estimated in this study were within the range of studies in other regions, however using other parameters resulted in important differences in expected biomass. These differences can have major implications in management, especially when estimating biomass availabe for harvest or predicting population size and effects on local ecosystems. Using site-specific values provides a more aqurate estimate of fish biomass. Future research should try to use, to the extent possible, parameters calculated for their region, or use different parameters to provide upper and lower bounds in their results. At the same time, this higlights the need for mor basic research that can describe allometric growth parameters -and other biologically important information- of lionfish throughout its invasion range.

While performing the lietrature review, it was often unclear if parameters presented for **eq.1** or **eq. 3**. Sometimes, they were even misslabeled and yielded senseless results when using the suggested conversion equation. On some others, parameters were said to be reported for mm to gr conversions, when they were actually reported as cm to gr conversions. Perhaps these minor discrepancies can be easily solved by any researcher, but why should they exist in the first place? It is important that we report our information in a standard way, making it readily available for other researchers but also managers. In this particular case, I provide my humble opinion in X simple guidelines to report allometric parameters:

1.

2. Be explicit in the methods section. What may seem obvious to you as an author -because you have been deeply immersed throughout the process- may not be clear to the reader. Specify any transformation performed on the data; When using log-transformations, mention the base used to transform. Do not asume that “data were log-transformed” means $log_{10}(X)$. These assumptions vary across disciplines and softwares. For example, in biology we often assume log-transformed indicates the use of base 10, however in R the command is log10() and not log(), which uses base e.

3. Use heteroskedastic-robust standard errors.

4. At the least, specify the equation for which parameters are presented and try include an explicit example with the parameters substituted into it, as done by [X Y y Z]. If possible, present the parameters in their exponential and linear form.

5. Report standard errors and confidence intervals arround the obtained estimates. Given that small changes in a, c, and b can result in important changes in estimated weight, it is important that we report uncertainty arround each parameter and not just general model fit (*i.e.* R^2). Additionally, make every possible effort to report at least 4 decimal points. If the journal has style guidelines about this, include full estimates in a table as supplementary material.

6. Make your data -and code- available. Even if this is not requited by the journal or publisher, you can use free cloud data storage services to make your research accessible to others. In times and countries where resources are limited, it is important that we take advantage of all open science tools that promote the advancement of knowledge. Ultimately, this fosters transparency, allows replicability of research, and can lead to collaborations.

While in this work I make reference to allometric growth parameters, these guidelines can easily be applied to other areas and disciplines. It is important

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

Finally, I provide a review of other weight-at-length studies -making them readily accessible for future research- and provide a set of guidelines to standardize the way in which allometric parameters should be reported to facilitate their use.

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 millimiters 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
Aguilar-Perera and Quijano-Puerto (2016)	472	3.0e-06	-5.5400	3.3000	0.9500	Both	5.0
Aguilar-Perera and Quijano-Puerto (2016)	67	1.0e-06	-5.9300	3.4700	0.9500	F	5.0
Aguilar-Perera and Quijano-Puerto (2016)	59	4.0e-06	-5.3800	3.2300	0.9500	M	5.0
Sandel et al. (2015)	458	3.6e-05	-4.4400	2.8100	NA	Both	NA
Chin, Aiken, and Buddo (2016)	419	2.8e-05	-4.5600	2.8500	0.8715	Both	18.3
Barbour et al. (2011)	774	2.9e-05	-4.5391	2.8900	NA	Both	27.0
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, Frazer, and Jacoby (2014)	1887	3.0e-06	-5.5229	3.2400	0.9700	Both	15.0
Sabido-Itza et al. (2016)	2143	5.0e-06	-5.2828	3.1832	0.9907	Both	0.5
Froese and 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

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

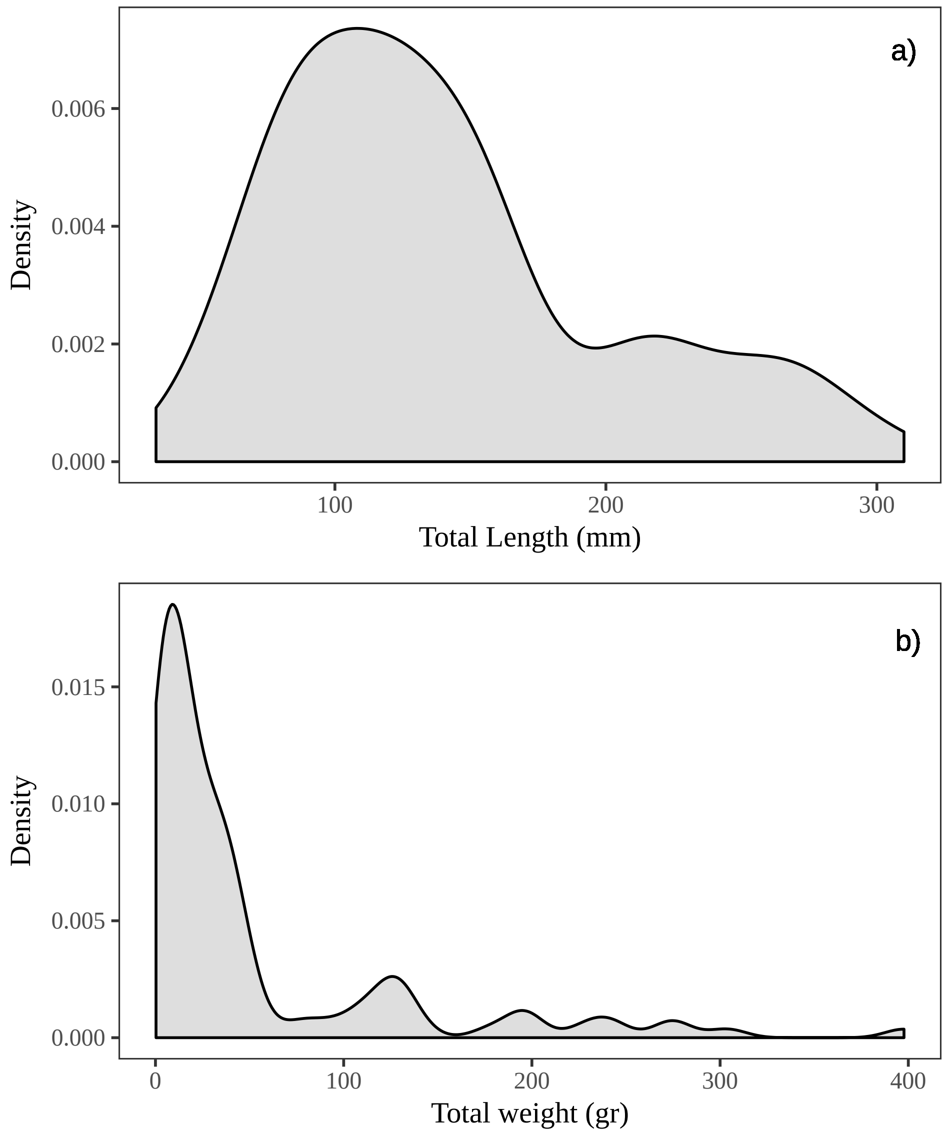

Figure 2: Kernell density plots for a) Total length (mm) and b) Total weight (gr) for 109 lionfish sampled off the coast of Puerto Aventuras, Mexico.

287 ## Scatter plot

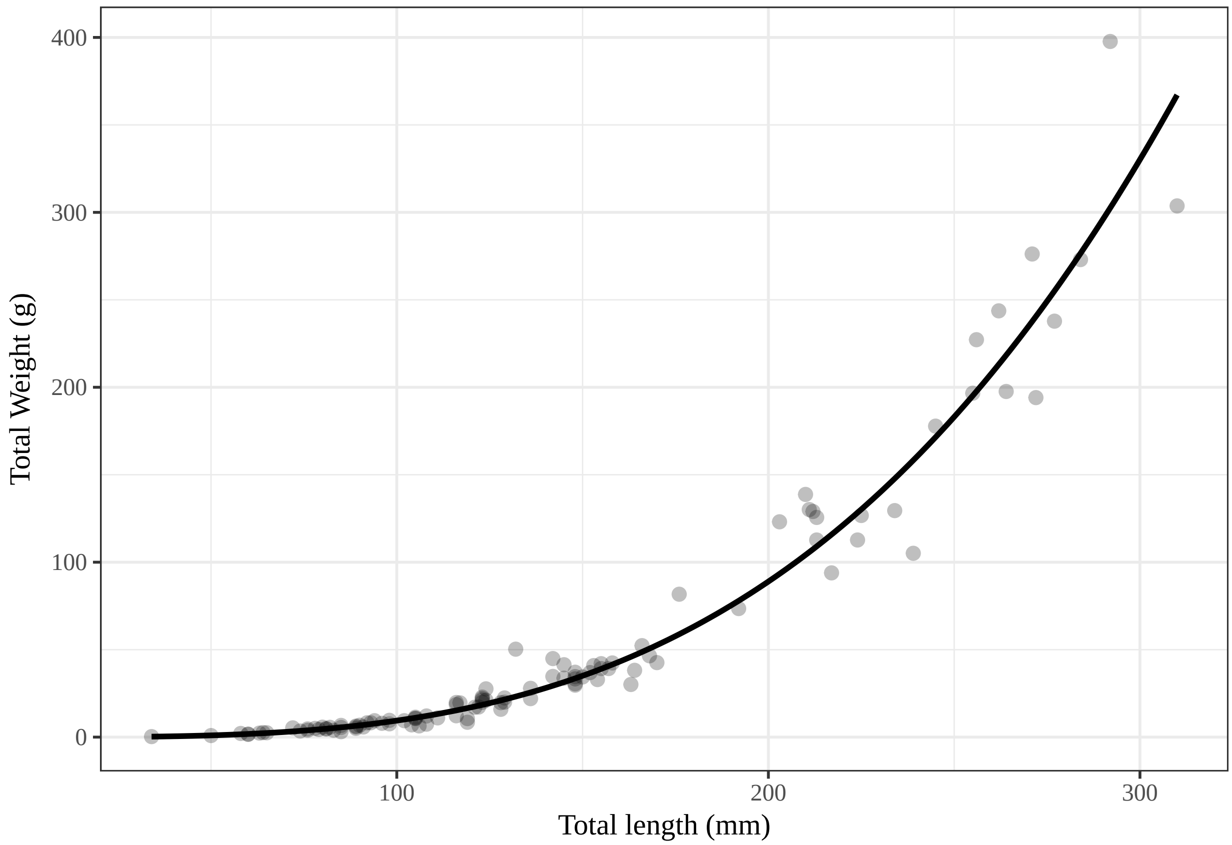

Figure 3: Weight-at-length relationship for 109 lionfish sampled off the coast of Puerto Aventuras, Mexico. Points indicate samples, solid line indicates curve of best fit.

Review plots

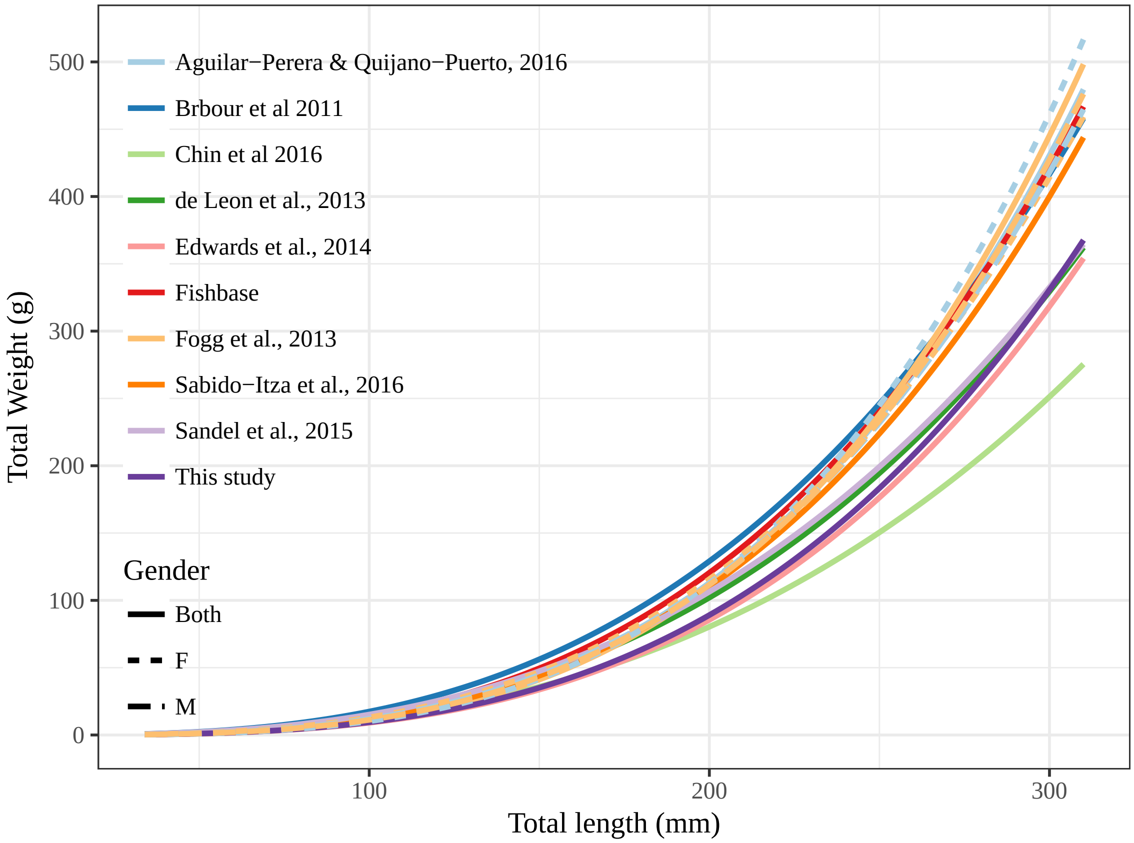

Figure 4: Weight-at-length relationships (n = 14) for eight studies, this study, and FishBase parameters. Colors indicate studies from which the parameters were extracted. Solid lines indicate that the fit was performed for males and females pooled together. Dotted lines indicate that the regression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

Predictions plot

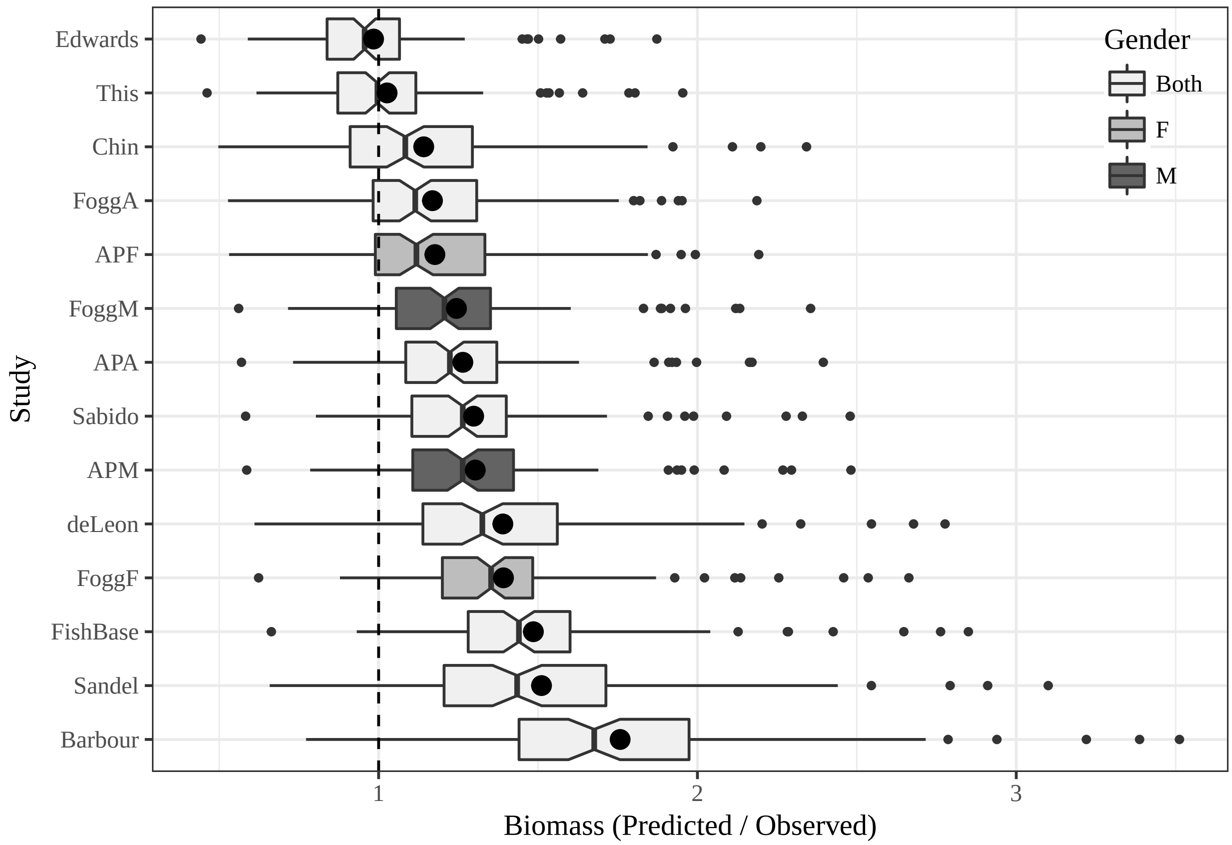

Figure 5: . Box and whiskers plot showing the distribution of predicted to observed Total Weight ratios for 14 pairs of allometric parameters. Lines indicate median values, circles indicate mean values, notches represent 95% confidence intervals arround the median, lower and upper hinges correspond to 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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