# LENGTH-WEIGHT RELATIONSHIPS FOR SEVERAL LARGE PELAGIC SHARKS FROM THE INDIAN OCEAN

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**Summary**

Fork length-dressed weight relationships on shark species (*Prionace glauca*, *Isurus oxyrinchus*, *Carcharhinus longimanus* and *Carcharhinus falciformis*) were obtained from 8,331 observations recorded at sea on longliners. Significance of the sex factor was specifically assessed using GLM procedures. Linear and non-linear fits of size-weight data by species were tested. The results obtained were compared with those values provided by other authors using equivalent type of data. Deviation of the predicted *versus* observer weights were also assessed. Both types of fits tested have provided similar results, their confidence intervals plotted are mostly overlapped and the equations obtained were generally within those confidence intervals. Predicted mean dressed weights at size by species were in most cases quite similar or just mimetic to those obtained using equations previously reported.

## 1. Introduction

Marine species exhibit differences in life-history traits related among other to body size, reproduction, age and growth (Cortés 2008). In the case of highly migratory pelagic sharks in particular the phases of their life are driven by a very complex behavior of vertical and horizontal migrations over time for selecting appropriate habitats related to the nursery period, feeding, maturation, mating, pregnancy, as well as for selecting areas of parturition and the protection of their litters.

Length-weight relationships are fundamental information to infer the age structure of the population, to calculate individual growth rates in weight as well as to model or quantify some other aspect of fish population dynamics. Additionally, length-weight relationships are also needed in some fleets to change the reported weight per fish into common size units for stock assessments. Although the length-weight relationships are regularly considered as a routine analysis, it was shown that they can provide in some cases important information about the ecology of the species (Froese 2006). Reducing any possible uncertainty regarding these biological parameters will thus contribute to reduce the whole uncertainty in the preparatory of catch at size (CAS) and catch at age (CAA) data by fleet and fleets combined as well as of the stock assessments.

The weight (W) of fishes regularly is exponentially related to their length (L) according to an equation $W = a\,L^{b}$, where *a* is the intercept and *b* is the slope of the log-transformed relation (Le Cren 1951**,** Froese 2006). The primary purpose of determining length-weight relationships is usually to define a biometric relationship that is representative of all individuals in the whole stock and relatively stable over time in these characteristics highly migratory species with a long life-span. However, the availability of the different sizes and genders to develop these relationships could not be achieved equally in all fleets or gears, such as in purse seiners *vs.* longliners in the case of tuna species because their different gear-size selectivity. In those cases, obtaining length-weight relationships specifically for each fleet-area-season may be useful for raising procedures in order to determine CAS figures for each fleet component, since not all fleets apply the same protocols to record data and process fish onboard, or different size ranges and biological characteristic of the fish could be obtained in each fleet (e.g. reproductive *vs.* feeding processes). All this factors among other later discussed would produce results with regularly slight differences in practice among studies when the same types of size-weight data are really used. However, some striking differences between authors could be sometimes provided and should be investigated.

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The comparison of the observed weight at size data between different fleets may point out differences in some cases probably caused by methodological inconsistencies among studies due to the different protocols of sampling implemented, or because the gutting or dressing protocols onboard or during landings are different among fishing actors or gears. So, the comparison of the observed or predicted weight at size among fleets could result different in some cases and especially when units other than round weight are considered in calculations.

Differences obtained by applying either type of statistical fits can be barely perceptible in practice when the coverage of the full size range (from juveniles to adults close to their asymptotic sizes) and ideally with the number of specimens being equally or proportionally distributed among the different size classes and genders. In other words, when the length-weight data sets are sufficiently robust in terms of the quality and quantity of observations and adequately represents the different areas, sexes and ranges of sizes present in the natural environment and/or those most frequently caught (Carroceda and Colmenero 2016). However, some studies do not provide very detailed descriptions of the type of length and weight used as well as other descriptive information. Since each fleet have different way of processing its catches during landings and/or onboard (not all fleets apply the same procedures to process fish and they can use different conversion factors among weight types) in addition to the fact that different terminologies or interpretations can be used in literature depending of the country, there have often caused misunderstanding or apparent discrepancies among studies or uncertainties on these length-weight parameters. Field manuals regularly include a variety of values but in some cases some most representative are omitted or misreported.

Several authors have already proposed equations to establish relationships between the length and weight of different shark species that could be representative for different stocks of respective oceans (e.g. Amorim *et al*. 1997, Arocha *et al*. 2005, Campana *et al*. 2005, Kohler *et al*. 1995, Mejuto and González-Garcés 1984, Espino *et al*. 2010, Mejuto *et al*. 2008). Following the guidelines of the Working Party of Ecosystems and Bycatch, the present paper provides various equations that let calculate the standard dressed weight (carcass) from standard fork length of several shark species. The objective is to estimate parameters of the weight and length relationships in four species of large pelagic sharks observed in areas of the Indian Ocean (*Prionace glauca*, *Isurus oxyrinchus*, *Carcharhinus longimanus* and *Carcharhinus falciformis*). The results achieved in the present paper are compared with those previous Fork length (FL) - Dressed weight (DW) relationships also described for the Indian Ocean as well as with some other relationships described in literature and considered as reference in some field manuals of other areas (Ariz *et al*. 2007, Espino *et al*. 2010, García-Cortés & Mejuto 2002, Mejuto *et al*. 2008; Santos *et al*. 2011).

## 2. Material and methods

In the present paper, length-weight records obtained over 18 years for scientific observers on board commercial vessels were used, providing a balanced representation of the sizes and sexes in longline fleets targeting swordfish (Mejuto *et al*. 2006, García-Cortés *et al*. 2008). Data was collected on several shark species (*Prionace glauca*, BSH; *Isurus oxyrinchus*, SMA; *Carcharhinus longimanus*, OCS and *Carcharhinus falciformis*, FAL), including the gender (sex) of the individuals.

The standard fork length size (FLcm) considered an independent variable was measured in a straight line mostly with tape or in some cases with calipers to the nearest lower centimeter, for 1 cm size categories defined by their lower limits. The corresponding carcass or dressed weight (DWkg) as the dependent variable was obtained onboard regularly using scales or 5-50 kg dynamometers (Kamoshita model). All DW information was obtained before the implementation of the fin-attached regulation of the EU[2]. So, records of DW used in the present paper do not include the weight of their fin-set because at that time they were previously separated from the trunks and the bodies and their respective fin-set were full retained, frozen and stored separately. Therefore, the head was severed from the body. The complete caudal fin was cut at the precaudal pit. Then the gut was removed from the anus to the head. So, in this case dressed weight (DW) is considered to be the weight of the specimens without head, viscera and the entire fin-set, except for blue shark species to which the 'bellies' are also removed. This protocol was regularly used in the past periods during regular commercial trips, without any bias resulting from the observer's criteria and probably used now for those flags-fleets whose fin-attached policy is not implemented. The gender (sex) of each fish was also recorded when feasible (F:females, M:males, T:F+M).

[2] Regulation (EU) Number 605/2013 of the European parliament and of the council of 12 June 2013.

The analysis of deviation GLM (R x64 4.1.2) was conducted beginning with only one intercept term and continuing fitting the additional effect of the variable size and the interaction between the variable gender (sex) and size, to test its significance and importance in the length-weight relationship by the difference in deviations obtained.

Based on the results of the analysis of deviation, relationships between length and weight of the type $DW_i$=a $(FL)_i^b * 10^{\varepsilon}{}_i$ where *a* and *b* are parameters and $10^{\varepsilon}{}_i$ is the multiplicative error term for the $i^{th}$ fish, were estimated. A logarithmic transformation was applied as first approximation to *linear fits*, where *a* and *b* are the constants for establishing these linear relationships (Sparre and Venema 1997). The constants *a* and *b*, as well as their confidence intervals, were estimated in this case with LM procedures. A second approximation was carried out using a *non-linear* fitting model (Anon 2009) and tested using the NLS R-function with the Marquardt estimation method (library minpack.lm 1.2-2) for the estimation of the constants *a* and *b*. Both analyzes were run on R x64 4.1.2.

The mean weight at size predicted from each equation was later compared and plotted *versus* the weights at size observed. The whole estimated weights from the set of size data-distribution used in the present paper was also compared with the whole weights observed in the same data set and also with those total weight predictions obtained from other studies also reported as FL and DW units.

## 3. Results

A total of 8,331 individuals of different shark species were analyzed: 5,039 BSH, 498 SMA, 1,387 FAL and 1,407 OCS.

### *3.1. Prionace glauca (BSH)*

A total of 5,039 specimens of blue shark (BSH) were analyzed of which 1,633 are females (73-291cm FL; 0.9-74.0 kg DW) and 3,406 males (78-287cm FL; 1.2-74.0 kg DW). **Figure 1** shows their size frequency distribution and the cumulative frequency by sex, in 5cm classes. The respective average sizes and weights of the observations were 183.33 cm (Std.= 27.66) and 18.96 kg (Std.= 8.75) for females and 185.78 cm (Std.= 35.19) and 19.7 kg (Std.= 11.85) for males. Size ranges were very similar between both sexes. The number of samples per size category was a good reflection of the sizes most frequently observed in the areas sampled.

The ANOVA result for the GLM model (logDW~logSize+logSize:SEX) shows that sex has little relevance in this length-weight relationship. The 99.7% of total deviation observed of the weight is explained by the size factor and only 0.3% of the deviation is explained by the combination of the size:sex (**table 1**).

**Table 2** shows the respective estimates *a* and *b* values resulting from the *linear regression* analysis LM (logDW~logSize) and the *non-linear regression* analysis NLS (DW~Size) applied to the data of males, females and females+males combined. In the case of the *linear fit*, a value $r^2$=0.8709 for females and $r^2$=0.9486 for males were obtained. For the total (females+males) a value $r^2$=0.9271was obtained. The equations and fits obtained are graphically represented in **figure 2**. Negligible differences in weight at size predictions are observed using the different equations achieved in the present paper. Additionally, the curves obtained with linear regression analysis by sex are within the 95% confidence interval of the linear curve obtained for all the specimens combined. On other hand, the constants *a* and *b* obtained from the *non-linear regression* analysis for the total (females+males) were 2.217642E-06 and 3.04425 respectively. **Figures 3** and **4** show the diagnoses of the residuals of the linear and non-linear analyzes for the total (females+males). Based on these results, it was not considered justifiable from the statistical viewpoint, plausible from the biological viewpoint or practical from an operational viewpoint to formulate size-weight equations by sex using this data set.

The comparison of equations obtained in the present analysis *versus* other published for the BSH species in the same weight-length type (DW~FL) are shown in **table 3** as well as the predicted DW values at size in **figure 5**. **Table 4** shows the percentage of discrepancy in predicted total dressed weight *versus* observed total dressed weight when applying the different length-weight relationships to the size data set used in the present document. The results indicate that the predicted total dressed weights were very similar among most equations tested, ranging in most cases between -3.01% and +1.51% in relation of the total observed dressed weight for such set of size data. However, one of the equation tested (Campana *et al.* 2005) from NW Atlantic showed a huge and positive systematic bias in predicted total DW *versus* other equations tested, reaching in that last case a mean weight overestimation of +79.62% *versus* the total dressed weight predictions from the other equations tested. When reviewing the last document cited it was found that, among the length-weight relationships provided by that author for BSH, there is one described as "dressed weight" (DW) including their corresponding constant values and a plot. That was the one selected from that paper giving rise to the enormous discrepancy in relation to those other tested. However, comparing other equation described by Campana *et al.* (2005) for FL-RW *versus* two other relationships also in FL-RW for the same BSH stock (e.g. Kohler *et al.* 1995, Mejuto *et al.* 2008) with insignificant difference between both last authors cited, it was noted that the discrepancies among the three authors compared were in fact negligible in the prediction of mean round weight (RW) by length classes, despite that the Campana's size data is reported in curve FL.

The discrepancy between curve and straight FL is expected to be a relatively minor problem in BSH species in particular compared to some other fish species and this difference in the type of FL would not be considered as sufficient reason in BSH to explain the enormous discrepancy in the predictions of the mean dressed weight at size compared to those obtained from other authors. Additionally, these differences in the predictions of DW by size could not be justified by differences between the length-weight relationships between the Atlantic and the Indian stocks, since their differences in mean RW at size are in fact negligible among authors. Therefore, except for unknown causes that could not be assessed, the huge discrepancy found in the prediction of DW at size using Campanas's equation *versus* the other relationships tested -apparently for the same "type of dressed weight"- could be likely due to the different type of DW used by that author for a particular fleet and during a specific period, compared to other types of DW recorded by the other authors in their respective fleets and periods. The high similarity among predictions in round weight using equations from the three authors and different areas it would support that the differences found in the Campana's equation in DW units *versus* other equations tested are not due to length-weight differences between the BSH stocks of the North Atlantic and the Indian Ocean.

This fact highlights how risky can be to generalize and apply a particular length-weight relationship obtained in a single fleet when the types of weight are not detailed described, the ways of processing catches on board are probably not the same between fleets-periods and the protocol of comparison are not previously verified among studies. However, discrepancies in the predicted DW between other authors tested in the present paper have provided minor or negligible differences in practice, suggesting that in those other cases the protocols of dressing during the respective periods described could likely be similar. Discrepancies among length-weight relationships are usually smaller when the types of weights considered among authors are in RW, the size ranges and frequencies are similar and the sampling protocols comparable or standardized among authors.

### *3.2. Isurus oxyrinchus*

A total of 498 specimens of shortfin mako (SMA) were analyzed, 215 are females (66-302 cm FL; 2.0-203.0 kg DW) and 283 males (64-252 cm FL; 2.0-130.0 kg DW). **Figure 6** shows their size frequency distribution and cumulative frequency by sex, in 5cm classes with a similar range of sizes for both sexes. The respective average sizes and weights of the observations were 166.81 cm (Std.= 42.03) and 42.67 kg (Std.= 27.38) for females and 177.69 cm (Std.= 35.63) and 47.65 kg (Std.= 22.02) for males. Size ranges were similar between both sexes. The number of samples per size category could be a good reflection of the sizes most frequently observed in the areas sampled.

The ANOVA result for the GLM model (logDW~logSize+logSize:SEX) shows that sex has little relevance in the length-weight relationship from this data set. The 99.996% of total deviation observed is explained by the length factor and only 0.004% of the deviation by the size:sex combination (**table 5**).

**Table 6** shows the estimates *a* and *b* values resulting from the *linear regression* analysis LM (logDW~logSize) and the *non-linear regression* analysis NLS (DW~Size) applied to the data of males, females and total (females+males). In the case of the linear fit, a value $r^2$=0.9764 for females and $r^2$=0.9713 for males were obtained. For the total (females+males) was obtained an $r^2$=0.9744. The equations obtained are represented graphically in **figure 7**. The constants *a* and *b* obtained from the non-linear regression analysis for the total (females+males), 1.0961E-05 and 2.93263 respectively, differ from their respective values obtained by linear fit, 1.6644E-05 and 2.85165. However the size-weight plot suggests that the fit obtained for prediction of the DW is within the confidence interval of weight at size linear predicted. The **figures 8** and **9** show the diagnoses of the residuals of the linear and non linear analyzes for the total (females+males). Based on these results, it was not considered justifiable from the statistical viewpoint, plausible form the biological viewpoint or practical from an operational viewpoint to formulate size-weight equations by sex using this data set.

A comparison between equations obtained in the present analyses against others published for SMA also in dressed weight is shown in **table 7** and **figure 10**. **Table 8** shows the percentage of discrepancy in total dressed weight predicted *versus* the total dressed weight observed when applying different length-weight relationships tested to the size data set used in the present paper. Very minor discrepancies in total weight estimations were obtained among equations in a range between +0.60% and -1.05%, suggesting similar predictions among equations and likely similar protocols of dressing in the different fleets described by the respective authors.

### *3.3. Carcharhinus falciformis*

A total of 1,387 specimens of silky shark (FAL) were analyzed of which 697 are females (59-290 cm FL; 1.0-90.0 kg DW) and 690 males (53-288 cm FL; 1.0-80.0 kg DW). **Figure 11** shows their size frequency distribution and cumulative frequency by sex, in 5cm classes. The respective average sizes and weights of the observations were 124.70 cm (Std.= 38.42) and 15.06 kg (Std.= 15.24) for females and 121.62 cm (Std.= 36.36) and 14.16 kg (Std.= 14.62) for males. Size ranges were very similar between sexes but different frequency distribution is suggested between males and females. The number of samples per size category was a good reflection of the sizes most frequently observed in the areas sampled.

The ANOVA result for the GLM (logDW~logSize+logSize:SEX) model shows that sex has no relevance in this length-weight relationship. The 100% of total deviation observed is explained by the length factor (**table 9**).

**Table 10** shows the estimates *a* and *b* values resulting from the *linear regression* analysis LM (logDW~logSize) and the *non-linear regression* analysis NLS (DW~Size) applied to the data of males, females and total (females+males). In the case of the linear fit, a value $r^2$=0.9038 for females and $r^2$=0.9061 for males were obtained. For the total (females+males) was obtained $r^2$=0.9048. The equations obtained are represented graphically in **figure 12**. The constants *a* and *b* obtained from the *non-linear regression* analysis for the total (females+males), 5.794761E-05 and 2.55614 respectively, differ from their respective values obtained by linear fit, 6.610192E-06 and 2.97421. However the plot suggests that the fit obtained for the prediction of the DW is within the confidence interval of the linear predicted weight at size. The **figures 13** and **14** show the diagnoses of the residuals of the linear and non linear analyzes for the total (females+males). Based on these results, it was not considered justifiable from the statistical viewpoint, plausible from the biological viewpoint or practical from an operational viewpoint to formulate size-weight equations by sex using this data set.

The comparison of the equations obtained in the present analysis *versus* others published for the FAL species in dressed weight are shown in **table 11** and **figure 15**. **Table 12** shows the percentage of discrepancy in total predicted weight *versus* observed weight when applying different length-weight relationships to the size data set used in the present document. Discrepancies among the equations tested were between -6.74% and +23.28%. The mayor positive difference was obtained when a very preliminary relationship provided in year 2002 using a lower number of observations was compared. However, the number of samples is higher in the present analysis as well as covering a broader size range.

### *3.4. Carcharhinus longimanus*

A total of 1,407 individuals of the oceanic whitetip shark (OCS) were analyzed, 1,008 females (63-232 cm FL; 1.6-90.0 kg DW) and 399 males (61-207 cm FL; 1.0-41.5 kg DW). The respective average sizes and weights of the observations were 127.80 cm (Std.= 35.32) and 15.96 kg (Std.= 13.61) for females and 114.24 cm (Std.= 30.03) and 9.34 kg (Std.= 7.34) for males. **Figure 16** shows their size frequency distribution and cumulative frequency by sex, in 5cm classes. Size ranges between sexes are similar. However, their size frequencies were different between sexes and especially for fish FL> 110 cm where females were predominant.

The ANOVA result for the GLM model (logDW~logSize+logSize:SEX) shows that sex has little relevance in the length-weight relationship. The 99.525% of total deviation observed is explained by the size factor and only 0.475% of the deviation is explained by the combination of the size:sex (**table 13**).

**Table 14** shows the estimates *a* and *b* values resulting from the *linear regression* analysis LM (logDW~logSize) and the *non-linear regression* analysis NLS (DW~Size) applied to the data of males, females and total (females+males). In the case of the linear fit, an $r^2$=0.9320 for females and $r^2$=0.9174 for males were obtained. For the total (females+males) was obtained an $r^2$=0.9271. The equations obtained are represented graphically in **figure 17**. The constants *a* and *b* obtained from the *non-linear regression* analysis for the total (females+males), 1.086301E-05 and 2.88110 respectively, differ from their respective values obtained by linear fit, 6.638045E-06 and 2.97229. However, the plot suggests that the fit obtained for the predictions of the dressed weight is within the confidence interval of the weights linear predicted at size. The **figures 18** and **19** show the diagnoses of the residuals of the linear and non linear analyzes for the total (females+males). Based on these results, it was not considered justifiable from the statistical viewpoint, plausible from the biological viewpoint or practical from an operational viewpoint to formulate size-weight equations by sex using this data set.

The comparison of the equations obtained in the present analysis against others published in dressed weight for the OCS species are shown in **table 15** and **figure 20**. **Table 16** shows the percentage of discrepancy in total predicted weight *versus* observed weight when applying different length-weight relationships to the size data set used in the present document. Discrepancies among the equations tested were between -3.01% and -0.03%.

*3.5. General Discussion*

Size-weight relationships based on the linearization of size and weight data are in some cases questioned. The discussion about different types of fits is usually focused more as a methodological refinement than for the real impact on the estimates of mean weights at size or for having a significant impact on the level of uncertainty in data preparatory and stock assessments. Linearization can be a good alternative in simple models that can be easily linearized, providing a unique solution based on the smallest sum of squares. Linearization could provide in most cases a good approximation in this type of biometric size-weight relationship when samples are robust and truly representative of the range of sizes and sexes present in the stock. In the case of non-linear models, incorrect specification of the model, poor initial starting values, insufficient data and/or insufficient interactions could affect convergence.

In the present paper, both types of fits tested have generally provided similar results for the different species considered when DW predictions at size have been achieved. Confidence intervals plotted are regularly overlapped and the different equations obtained and tested were within those confidence intervals. Therefore, the fitting methods applied in these cases had a marginal impact in practice on the mean DW predictions from the size distribution considered in the present data set.

In general, the predicted mean dressed weights at size were in practice similar to those obtained using equations previously provided by other authors. However, two exceptions could be pointed out (see previous chapters). The case of the Campana's DW relationship for BSH species should be investigated because their DW at size predictions are largely positive from those obtained using equations of other authors and those provided in the present paper, reaching in that case a mean overestimation of 78% in relation to mean predicted DW at size from other equation tested. One possible explanation of such huge discrepancy in the predicted DW at size, as well as in the total dressed weight prediction from the size distribution, is describe in the BSH chapter (3.1.) of the present paper.

Biometric relationships are usually inherited traits that rarely differ significantly in a relatively short term within and between large pelagic fish stocks with parallel or related evolutionary histories. However, it has been argued that habitat conditions can in some cases modify these relationships. A special case was postulated in some large shark species perhaps during very specific parts of the life cycle or when very unfavorable habitat conditions occur lasting throughout the lifetime of individuals, such as a lack of prey in some particular areas of distribution, or during and after their concentration for biological processes involving a high energy cost, such as mating, pregnancy and parturition. In that sense, it was argued that weights at size in some shark's individual may differ depending on factors such as the amount of stomach contents, the stage of maturity-pregnancy or the liver weight. The livers store high energy as a food reserve and affect the buoyancy required during different live-stages. In that sense, variation in the liver size was accounted for majority of the weight difference in some shark individuals of the same species with corresponding lengths (Kohler *et al*. 1995). Moreover, in the case of highly migratory sharks some of the postulated differences are likely mitigated in some extend by accessing to food and appropriate habitat characteristics in a wide range of areas and depths thanks to their huge capacities for horizontal and vertical migrations, as well as the adaptability and their widely diverging opportunistic feeding patterns and their respective buoyancy requirement during the different biological stages throughout their lives. In some cases such as SMA the reproduction and pregnancy is expected to be even a minor factor for explaining the diversity of the length-weight relationships achieved by the different authors when sampling is diverse, since the fraction of population sampled in reproductive processes had regularly been very scarce or negligible in most studies consulted (García-Cortés *et al.* 2021). However, when the weights are in dressed, without livers and other parts of the fish, such difference between DW at equal size would be reduced among individuals.

The possible or apparent difference between size-weight relationships among authors is not in some cases easy to verify from literature given the very different ranges of sizes and number of observations at size are found in each stock and in the catches of the respective fleets-gears. Even when the same methodological approaches are apparently used, differences could be explained by the different size ranges among studies or other conditioning limitations related to the sampling protocols and the quality of the data recorded. Differences among authors are usually slight in practice when "equivalent data" are really used. In other cases, there are substantial methodological differences between authors in the way they obtain field data, defining criteria for analysis, deleting data they consider to be outliers, etc., or assuming sizes and/or weights types that are not strictly equivalent among studies. In this sense, the comparison of the observed weight at size data between different fleets or sources of data point out in some cases significant differences which are probably caused by methodological inconsistencies between the respective sampling protocols onboard or during landings (see e.g. Hanke *et al.* 2019). Whatever the cause, the representativeness of observations regarding the size-weight intervals considered in each case can make an important contribution to the differences between studies, especially when data are compared for fleets and gear with very different selectivity patterns (e.g. longline *vs*. harpoon, or longline *vs.* purse seiner), so that different size intervals and frequencies, sex, or biological stages could be analyzed by the respective authors.

In some cases, obtaining size-weight relationships for each fleet/area/season may have a practical application as they can be useful for domestic raising procedures in order to determine CAS figures for each fleet. In such cases, each relationship could be representing to the sizes and biological characteristics of those individuals caught by a particular fleet when they target fish with specific features and/or there are significant, relevant and verified differences *versus* the mean values observed for the whole stock. The different proportion of genders in the samples could be in some cases another potential source of size-weight diversity in large pelagic species when the size:sex interaction is identify as a significant factor for explaining the weight variability observed. However, in the case of the species and sizes considered in the present paper, the significance of sex seems to be irrelevant or negligible when the same size ranges by sex are compared using the size:sex combinations into the GLM models. Special care must be taken when modeling sex as main factor in the case of those species with differential growth by sex, showing a different prevalence of one sex between different size ranges. Sometimes, the apparent significance of the sex as a main factor is just the result that only one sex is predominant or unique in certain size-weight ranges, and particularly in the largest size components of the population.

Another element receiving little attention in comparisons between size-weight relationships is the definition of the size categories used for each study and their subsequent use to compare predictions of weights according to size category used. In many species the size-weight relationships are often obtained assuming size intervals of 1 cm, generally represented (labeled) by their lower limit. However, in subsequent applications or comparisons the 5 cm intervals could be regularly used. This implies that to predict the average weight corresponding to each 5 cm size class the equation must be modified: $RW=a*(LJFL+k)^b$, *k* being a constant according to the size interval used for the size-weight fit, this constant being properly adapted to larger size categories defined to predict their mean weight by size category.

The different ways of processing the catches when units other than live weight are used is a key element that frequently contributes to the confusion and the diversity of relationships between studies, while constant conversion factors may be used in some other cases before fitting procedures. However, the results of the present papers suggest that differences among most studies tested were *de facto* minor, but with an important exception previously discussed on the BSH chapter. Subsequent studies on length-weight relationships should incorporate detailed descriptions of the type of size and weight used in each case and, in the event of using weights other than live or round weight, relationships by fleet are especially recommended and should be evaluated before to combine data sets. A special caution must be considered in the case of using or combining data sampled in different fleets since it is likely that those records could contain not only the DW of the bodies, but also the weight of their fin-sets naturally attached in some cases.

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Table 1. Result of the ANOVA of the BSH GLM (logDW~logSize+logSize:SEX) model.

```
Analysis of Deviance Table
Model: Gaussian, link: identity
Response: logDW
Terms added sequentially (first to last)
            Df Deviance Resid. Df Resid. Dev
NULL                         5038    1667.28
logSize      1  1545.78      5037     121.50
logSize:SEX  1     3.69      5036     117.81
```

Table 2. Results of the linear and non-linear analyses for the BSH species.

| Analysis | Data | a | b |
|---|---|---|---|
| Linear | Male | 1.546336E-06 | 3.10782 |
| Linear | Female | 7.536012E-06 | 2.81473 |
| Linear | Female+Male | 2.331003E-06 | 3.03269 |
| Non-Linear | Male | 1.532772E-06 | 3.11156 |
| Non-Linear | Female | 4.923344E-06 | 2.89769 |
| Non-Linear | Female+Male | 2.217642E-06 | 3.04425 |

Table 3. List of equations DW~FL for the BSH.

| Reference | Relationships | Geographical zone | n | Length range |
|---|---|---|---|---|
| García-Cortés & Mejuto, 2002 | $DW=0.00000160945*FL^{3.09904}$ | Indian Ocean (central zone) | 289 (147♀, 142♂) | 150 - 260 cm |
| Campana *et al.*, 2005 | $DW=0.0000017*FL^{3.205}$ | North-western Atlantic (Canada) | 382 | ----- |
| Ariz *et al.*, 2007 | $DW=0.00000040189*FL^{3.3620}$ | SW Indian Ocean (25ºS-35ºS, 30ºE-50ºE) | 2129 (374♀, 1704♂) | 82 - 352 cm |
| Mejuto *et al.*, 2008 | $DW=0.000001209*FL^{3.15789}$ | NE Atlantic Ocean | 119 | 93 - 254 cm |
| Espino *et al.*, 2010 | $DW=0.00000190154*FL^{3.07615}$ | Indian Ocean | 164 | 93 - 253 cm |
| Santos *et al.*, 2011 | $DW=0.0000009016*FL^{3.2048}$ | SW Indian Ocean (25-33ºS, 40-65ºE) | 447 (207♀, 240♂) | 132 - 283 cm |
| Present study – LM | $DW=0.000002331003*FL^{3.03269}$ | Indian Ocean | 5039 (1633♀, 3406♂) | 73 - 291 cm |
| Present study – NLS | $DW=0.000002217642*FL^{3.04425}$ | Indian Ocean | 5039 (1633♀, 3406♂) | 73 - 291 cm |

Table 4. Weight discrepancies in percentage between the predicted and the observed total weights, applying different relationships to the size data set (BSH) of the present document.

| a | b | Reference | %Pct |
|---|---|---|---|
| 1.60945E-06 | 3.09904 | García-Cortés & Mejuto, 2002 | -3.01 |
| 1.7E-06 | 3.205 | Campana *et al.*, 2005 | +79.62 |
| 4.0189E-07 | 3.3620 | Ariz *et al.*, 2007 | -2.37 |
| 1.209E-06 | 3.15789 | Mejuto *et al.*, 2008 | -0.48 |
| 1.90154E-06 | 3.07615 | Espino *et al.*, 2010 | +1.51 |
| 9.016E-07 | 3.2048 | Santos *et al.*, 2011 | -4.84 |
| 2.331003E-06 | 3.03269 | Present study - LM | -1.15 |
| 2.217642E-06 | 3.04425 | Present study - NLS | -0.03 |

Table 5. Result of the ANOVA of the SMA, GLM (logDW~logSize+logSize:SEX) model.

```
Analysis of Deviance Table
Model: gaussian, link: identity
Response: logDW
Terms added sequentially (first to last)

            Df Deviance Resid. Df Resid. Dev
NULL                          497    308.098
logSize      1  300.224       496      7.874
logSize:SEX  1    0.012       495      7.862
```

Table 6. Results of the linear and non-linear analyses for the SMA species.

| Analysis | Data | a | b |
|---|---|---|---|
| Linear | Male | 1.685136E-05 | 2.84843 |
| Linear | Female | 1.608296E-05 | 2.85950 |
| Linear | Female+Male | 1.664430E-05 | 2.85165 |
| Non Linear | Male | 1.607817E-05 | 2.85870 |
| Non Linear | Female | 9.263522E-06 | 2.96655 |
| Non Linear | Female+Male | 1.096074E-05 | 2.93263 |

Table 7. List of equations DW~FL for the SMA.

| Reference | Relationships | Geographical zone | n | Length range |
|---|---|---|---|---|
| García-Cortés & Mejuto, 2002 | $DW=0.0000141832*FL^{2.88231}$ | Indian Ocean (central zone) | 171 (107♀, 64♂) | 105 - 235 cm |
| Ariz *et al.*, 2007 | $DW=0.0000067236*FL^{3.0239}$ | SW Indian Ocean (25ºS-35ºS, 30ºE-50ºE) | 327 (184♀, 127♂) | 75 - 243 cm |
| Mejuto *et al.*, 2008 | $DW=0.00000256783*FL^{3.21031}$ | South Atlantic Ocean | 34 | 95 - 222 cm |
| Present study - LM | $DW=0.00001664430*FL^{2.85165}$ | Indian Ocean | 498 (215♀, 283♂) | 64 - 302 cm |
| Present study - NLS | $DW=0.00001096074*FL^{2.93263}$ | Indian Ocean | 498 (215♀, 283♂) | 64 - 302 cm |

Table 8. Weight discrepancies in percentage between the predicted and observed total weights, applying different relationships to the size data set (SMA) of the present document.

| a | b | Reference | %Pct |
|---|---|---|---|
| 1.41832E-05 | 2.88231 | García-Cortés & Mejuto, 2002 | -0.72 |
| 6.7236E-06 | 3.0239 | Ariz *et al.*, 2007 | -1.05 |
| 2.56783E-06 | 3.21031 | Mejuto *et al.*, 2008 | +0.60 |
| 1.664430E-05 | 2.85165 | Present study - LM | -0.81 |
| 1.096074E-05 | 2.93263 | Present study - NLS | -0.09 |

Table 9. Result of the ANOVA of the FAL GLM (logDW~logSize+logSize:SEX) model.

```
Analysis of Deviance Table
Model: gaussian, link: identity
Response: logDW
Terms added sequentially (first to last)

            Df Deviance Resid. Df Resid. Dev
NULL                         1386    1108.12
logSize      1   1002.7      1385     105.41
logSize:SEX  1      0.0      1384     105.41
```

Table 10. Results of the linear and non-linear analyses for the FAL species.

| Analysis | Data | a | b |
|---|---|---|---|
| Linear | Male | 4.985378E-06 | 3.03347 |
| Linear | Female | 8.585560E-06 | 2.91954 |
| Linear | Female+Male | 6.610192E-06 | 2.97421 |
| Non Linear | Male | 6.351687E-05 | 2.54025 |
| Non Linear | Female | 5.208459E-05 | 2.57508 |
| Non Linear | Female+Male | 5.794761E-05 | 2.55614 |

Table 11. List of equations DW~FL for the FAL.

| Reference | Relationships | Geographical zone | n | Length range |
|---|---|---|---|---|
| García-Cortés & Mejuto, 2002 | $DW=0.0000113294*FL^{2.91484}$ | Indian Ocean (central zone) | 411 (205♀, 206♂) | 50 - 220 cm |
| Ariz *et al.*, 2007 | $DW=0.000012977*FL^{2.8323}$ | SW Indian Ocean (25ºS-35ºS, 30ºE-50ºE) | 94 (40♀, 53♂) | 97 - 269 cm |
| Present study- LM | $DW=0.000006610192*FL^{2.97421}$ | Indian Ocean | 1387 (697♀, 690♂) | 53 - 290 cm |
| Present study- NLS | $DW=0.00005794761*FL^{2.55614}$ | Indian Ocean | 1387 (697♀, 690♂) | 53 - 290 cm |

Table 12. Weight discrepancies in percentage between the predicted and observed total weights, applying different relationships to the size data set (FAL) of the present document.

| a | b | Reference | %Pct |
|---|---|---|---|
| 1.13294E-05 | 2.91484 | García-Cortés & Mejuto, 2002 | +23.28 |
| 1.2977E-05 | 2.8323 | Ariz *et al.*, 2007 | -6.74 |
| 6.610192E-06 | 2.97421 | Present study - LM | -3.03 |
| 5.794761E-05 | 2.55614 | Present study - NLS | +4.39 |

Table 13. Result of the ANOVA of the OCS GLM (logDW~logSize+logSize:SEX) model.

```
Analysis of Deviance Table
Model: gaussian, link: identity
Response: logDW
Terms added sequentially (first to last)

            Df Deviance Resid. Df Resid. Dev
NULL                         1406     989.41
logSize      1   917.37      1405      72.03
logSize:SEX  1     4.38      1404      67.65
```

Table 14. Results of the linear and non-linear analyses for the OCS species.

| Analysis | Data | a | b |
|---|---|---|---|
| Linear | Male | 2.097672E-05 | 2.70989 |
| Linear | Female | 5.824073E-06 | 3.00643 |
| Linear | Female+Male | 6.638045E-06 | 2.97229 |
| Non-Linear | Male | 6.761644E-05 | 2.47425 |
| Non-Linear | Female | 1.018966E-05 | 2.90229 |
| Non-Linear | Female+Male | 1.086301E-05 | 2.88110 |

Table 15. List of equations DW~FL for the OCS.

| Reference | Relationships | Geographical zone | n | Length range |
|---|---|---|---|---|
| García-Cortés & Mejuto, 2002 | $DW=0.00000298446*FL^{3.15417}$ | Indian Ocean (central zone) | 567 (553♀, 14♂) | 65 - 215 cm |
| Ariz *et al.*, 2007 | $DW=0.000080431*FL^{2.4478}$ | SW Indian Ocean (25ºS-35ºS, 30ºE-50ºE) | 131 (41♀, 89♂) | 94 - 243 cm |
| Present study- LM | $DW=0.000006638045*FL^{2.97229}$ | Indian Ocean | 1407 (1008♀, 399♂) | 61 - 232 cm |
| Present study- NLS | $DW=0.00001086301*FL^{2.88110}$ | Indian Ocean | 1407 (1008♀, 399♂) | 61 - 232 cm |

Table 16. Weight discrepancies in percentage between the predicted and observed total weights, applying different relationships to the size data set (OCS) of the present document.

| a | b | Relationship | %Pct |
|---|---|---|---|
| 2.98446E-06 | 3.15417 | García-Cortés & Mejuto, 2002 | -3.01 |
| 8.0431E-05 | 2.4478 | Ariz *et al.*, 2007 | -2.37 |
| 6.638045E-06 | 2.97229 | Present study - LM | -1.15 |
| 1.086301E-05 | 2.88110 | Present study - NLS | -0.03 |

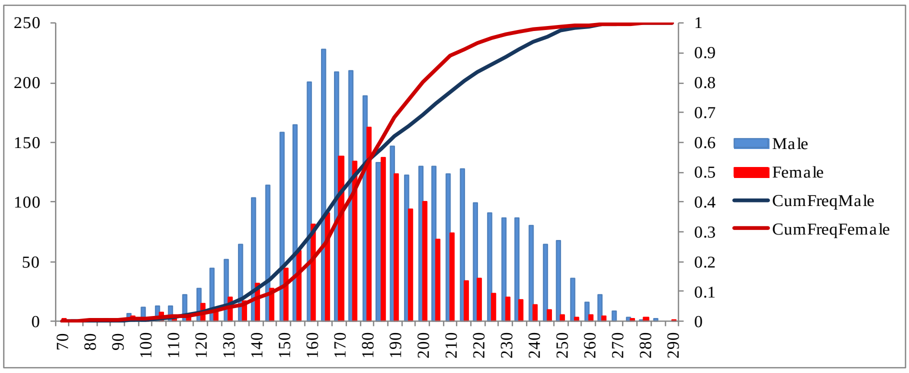


Figure 1. Distribution of sizes by sex of BSH and cumulative frequency.

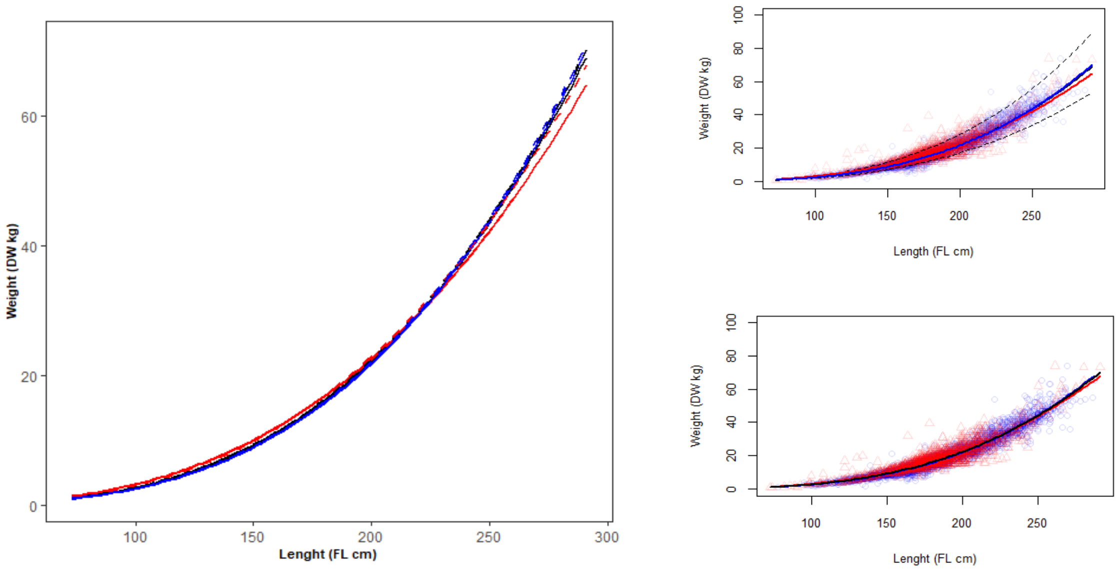


Figure 2. Length (FL cm) – dressed (DW kg) linear relationships of blue shark (BSH) from the Indian Ocean. Left panel: solid line=linear model, dashed line=non-linear model. Upper right panel: linear model per sex + 95% confidence intervals sex combined. Bottom right panel: non-linear model per sex. Colors: blue=males, red=females, black=females+males.

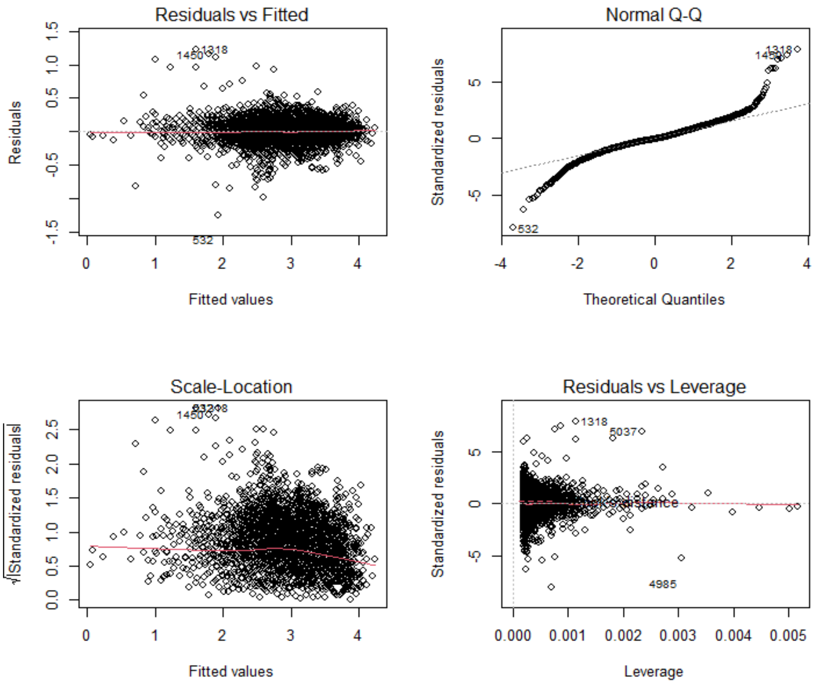


Figure 3. Diagnosis of the residuals of the size (FL cm)–dressed weight (DW kg) linear relationship of blue shark (BSH) from Indian Ocean stock. Residuals *vs.* fitted values, qq-plot and residuals *vs.* leverage.

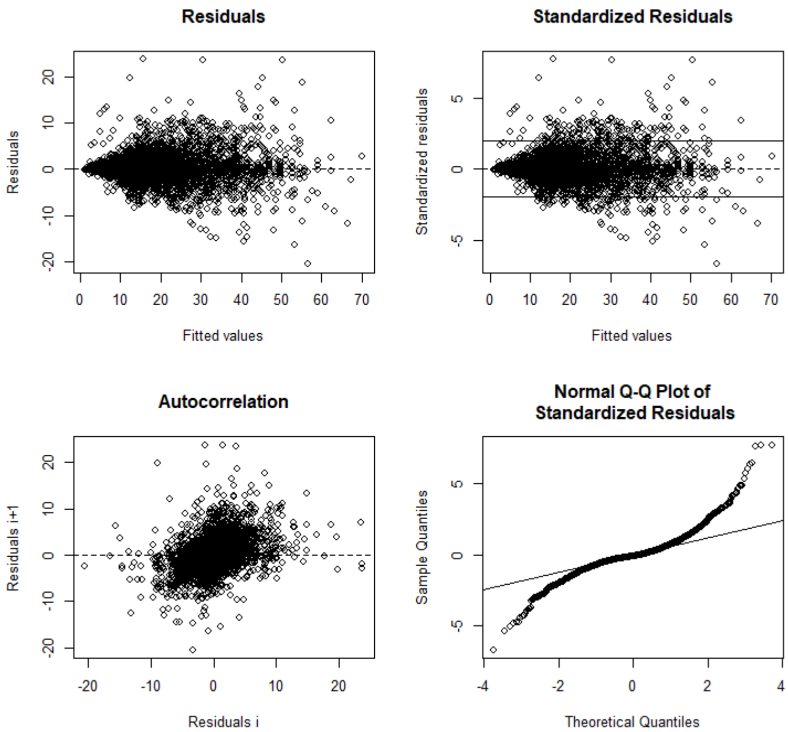


Figure 4. Diagnosis of the residuals of the size (FL cm)–dressed weight (DW kg) non linear relationship of blue shark (BSH) from Indian Ocean stock.

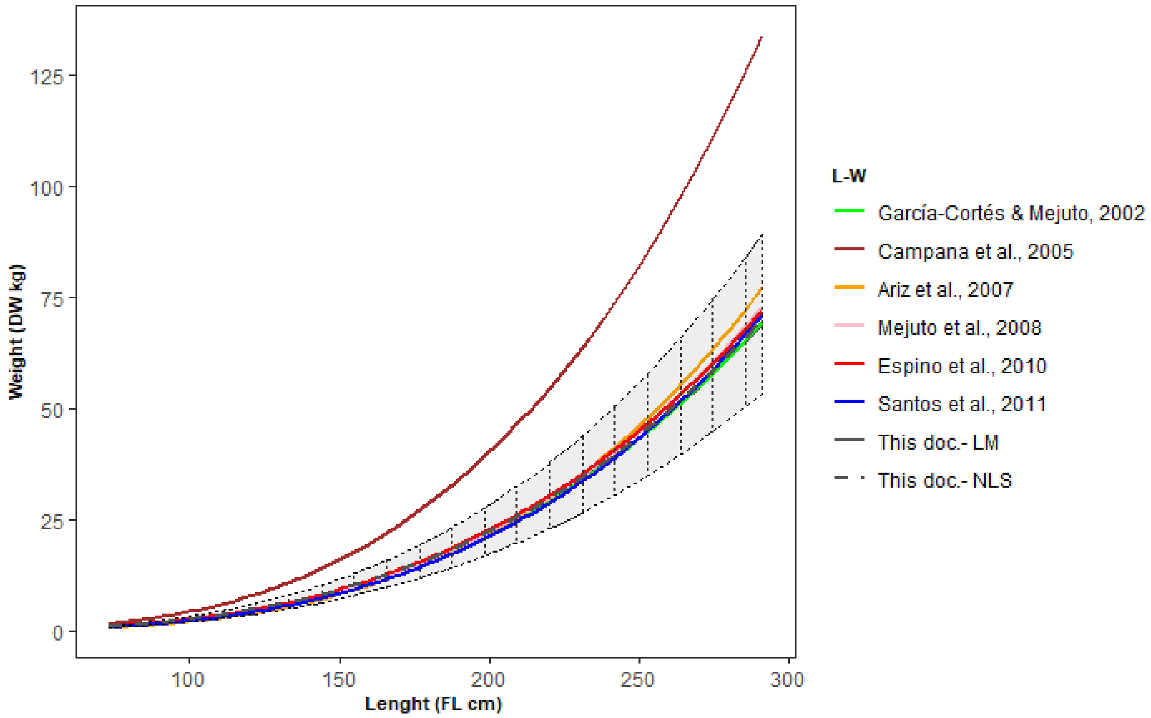


Figure 5. Fitting of DW~FL published equations for BSH *versus* the equations obtained by the present analyzes. Gray shading=95%CI LM analysis of this document.

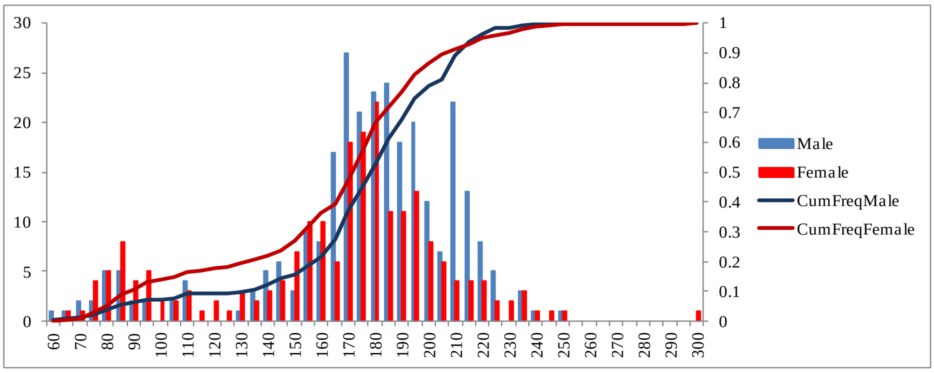


Figure 6. Distribution of sizes by sex of SMA and cumulative frequency.

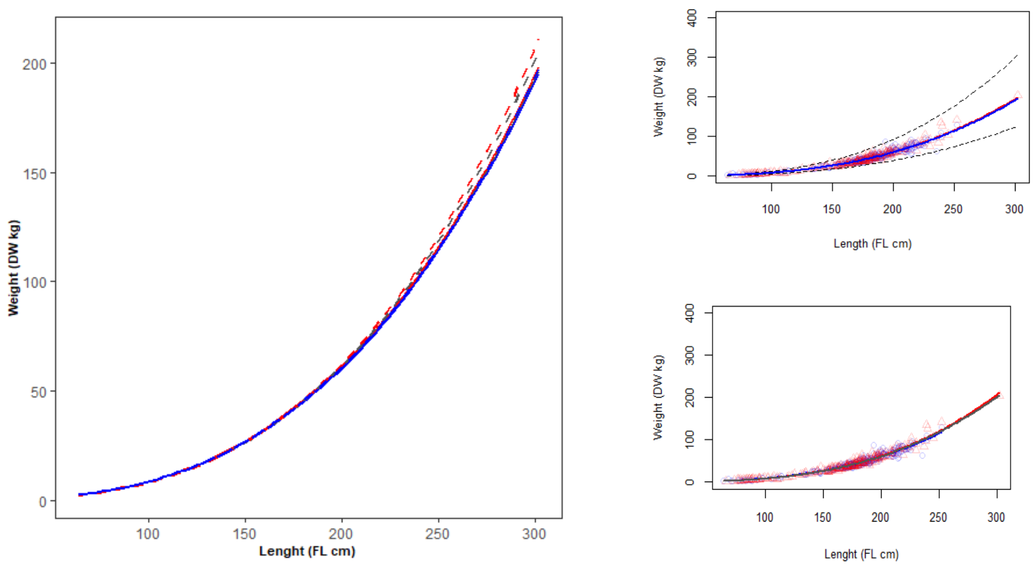


Figure 7. Length (FL cm) – dressed (DW kg) linear relationships of shortfin mako (SMA) from the Indian Ocean. Left panel: solid line=linear model, dashed line=non-linear model. Upper right panel: linear model per sex + 95% confidence intervals sex combined. Bottom right panel: non-linear model per sex. Colors: blue=males, red=females, black=females+males.

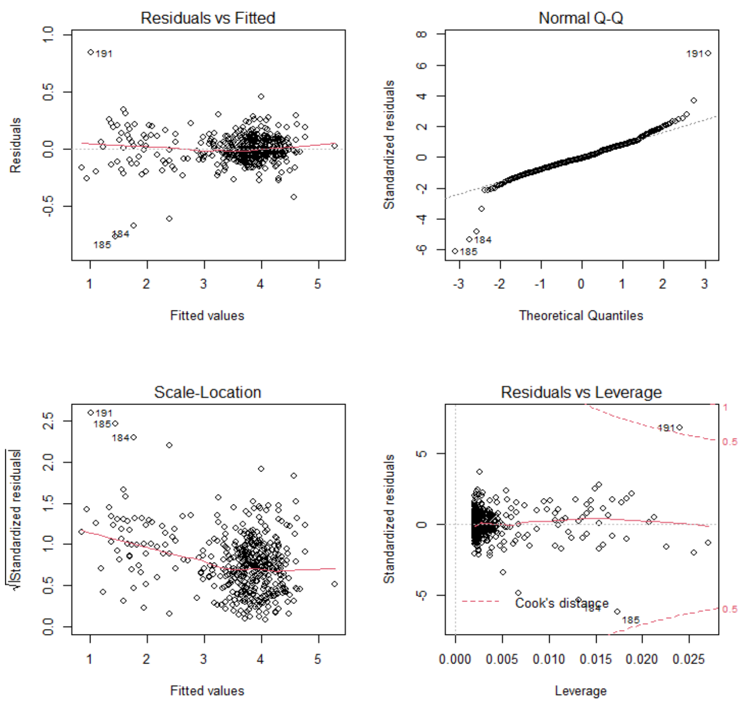


Figure 8. Diagnosis of the residuals of the size (FL cm)–dressed weight (DW kg) linear relationship of shortfin mako (SMA) from Indian Ocean stock. Residuals *vs.* fitted values, qq-plot and residuals *vs.* leverage.

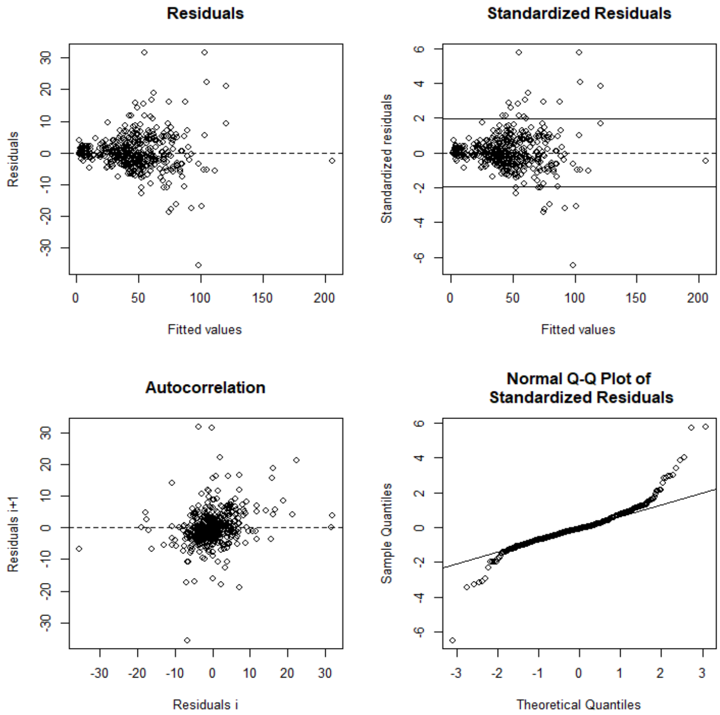


Figure 9. Diagnosis of the residuals of the size (FL cm)–dressed weight (DW kg) non linear relationship of shortfin mako (SMA) from Indian Ocean stock.

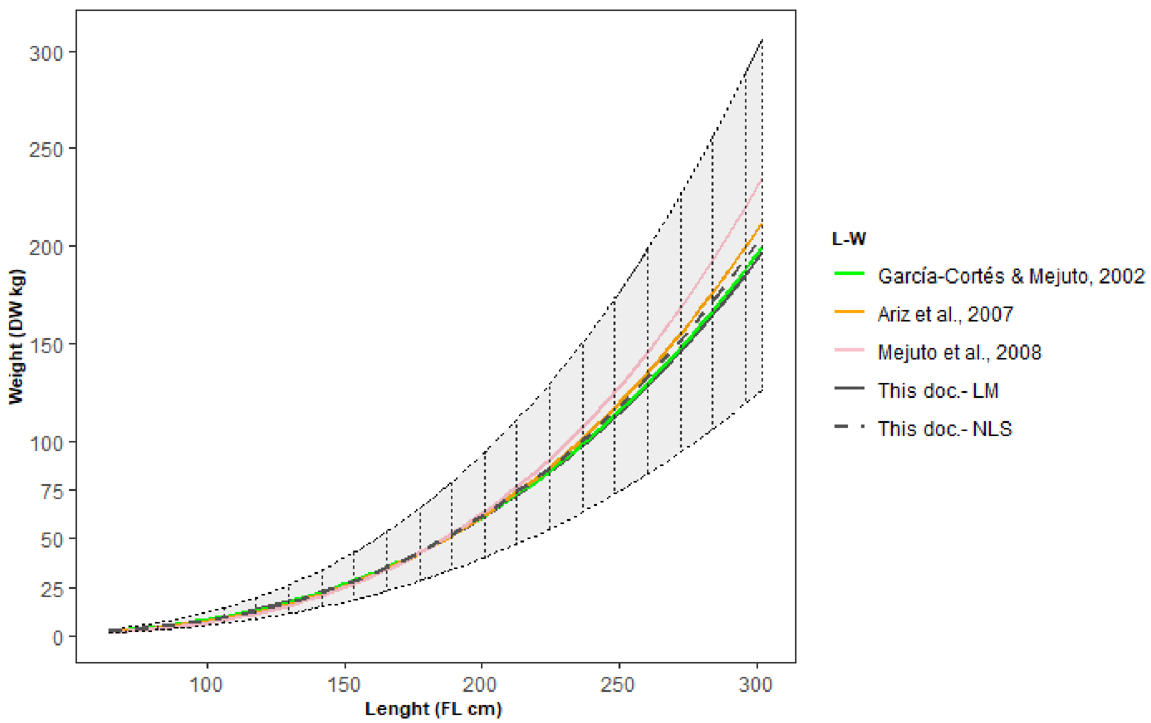


Figure 10. Fitting of DW~FL published equations for SMA *versus* the equations obtained by the present analyzes. Gray shading=95%CI LM analysis of this document.

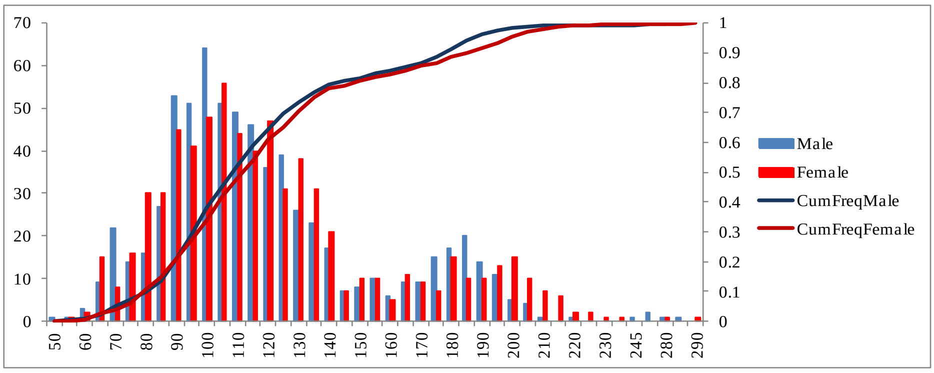


Figure 11. Distribution of sizes by sex of FAL and cumulative frequency.

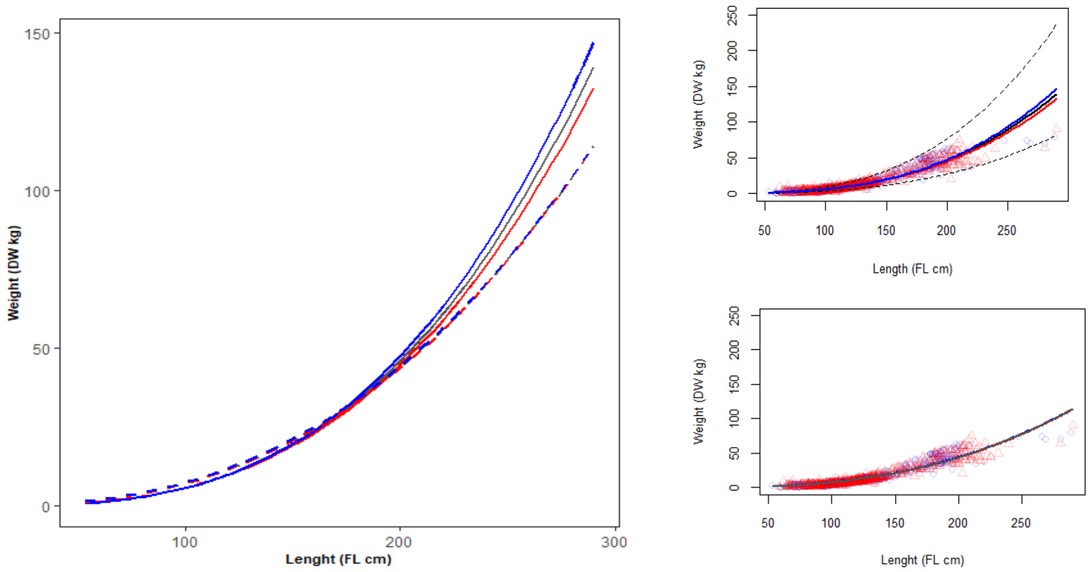


Figure 12. Length (FL cm) – dressed (DW kg) linear relationships of silky shark (FAL) from the Indian Ocean. Left panel: solid line=linear model, dashed line=non-linear model. Upper right panel: linear model per sex + 95% confidence intervals sex combined. Bottom right panel: non-linear model per sex. Colors: blue=males, red=females, black=females+males.

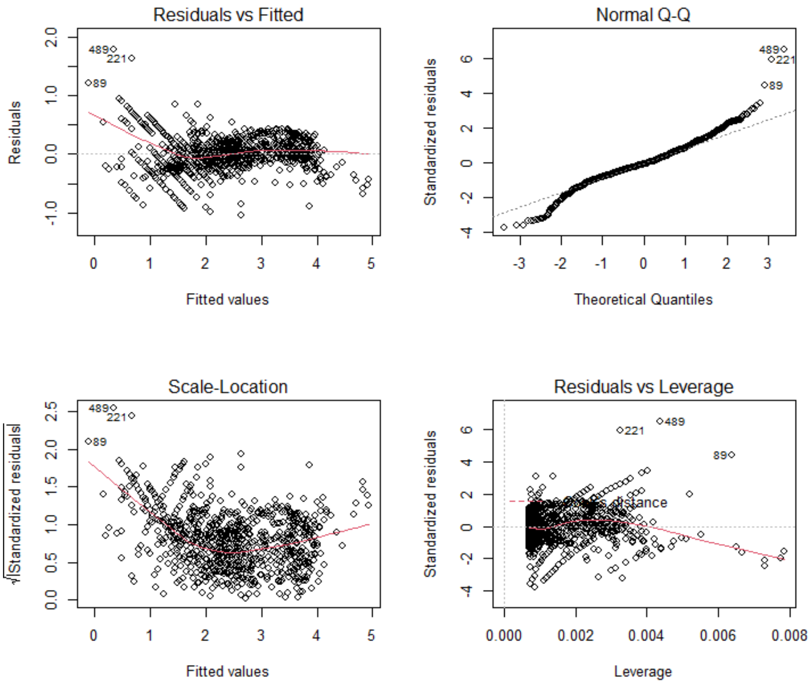


Figure 13. Diagnosis of the residuals of the size (FL cm)–dressed weight (DW kg) linear relationship of silky shark (FAL) from Indian Ocean stock. Residuals *vs.* fitted values, qq-plot and residuals *vs.* leverage.

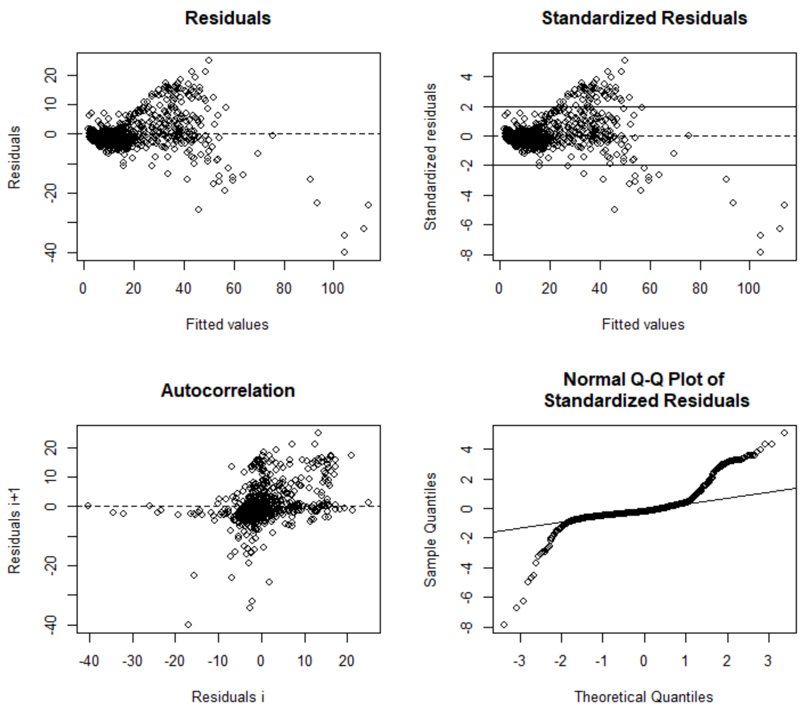


Figure 14. Diagnosis of the residuals of the size (FL cm)–dressed weight (DW kg) non-linear relationship of silky shark (FAL) from Indian Ocean stock.

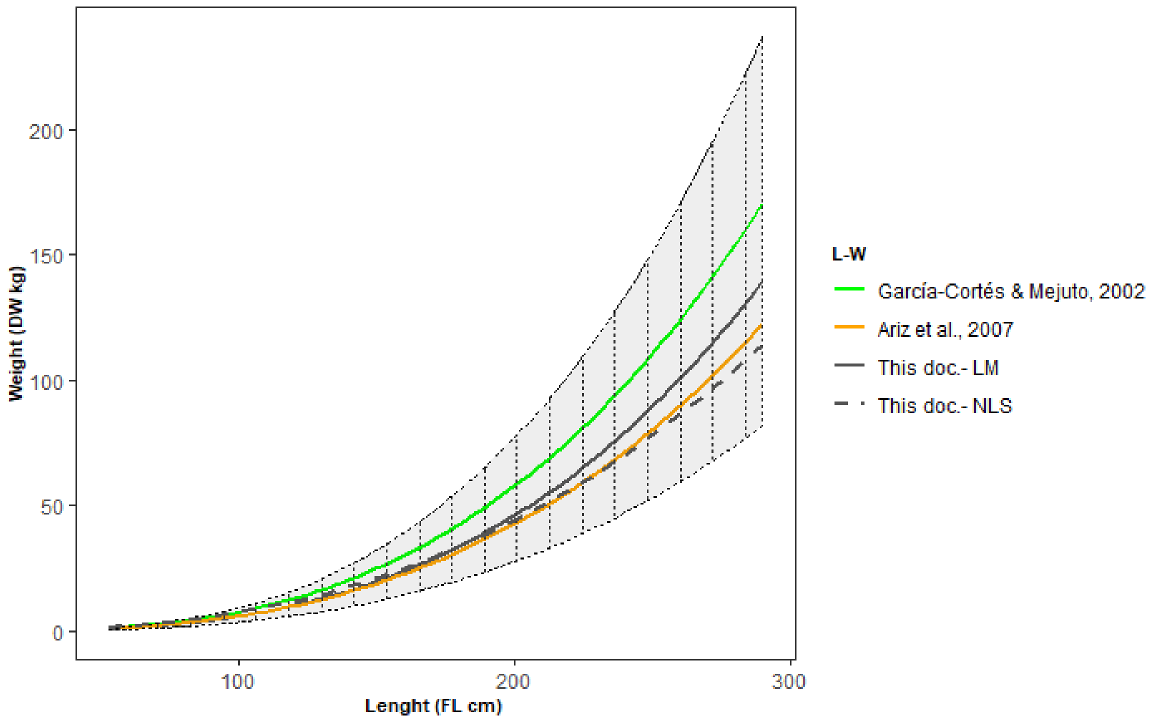


Figure 15. Fitting of DW~FL published equations for FAL *versus* the equations obtained by the present analyzes. Gray shading=95%CI LM analysis of this document.

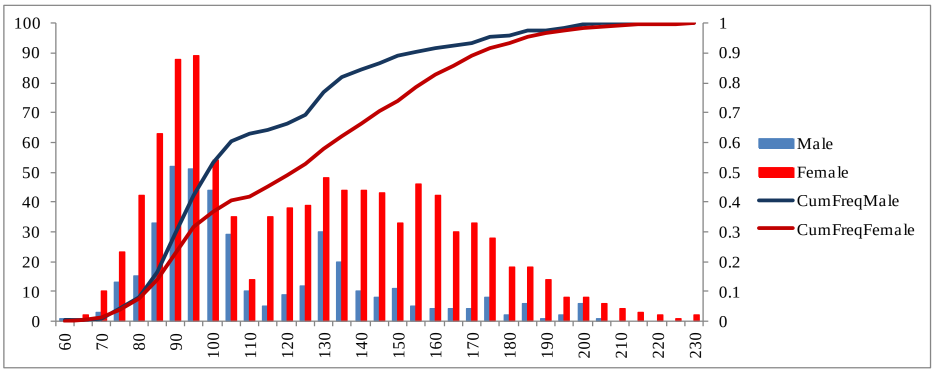


Figure 16. Distribution of sizes by sex of OCS and cumulative frequency.

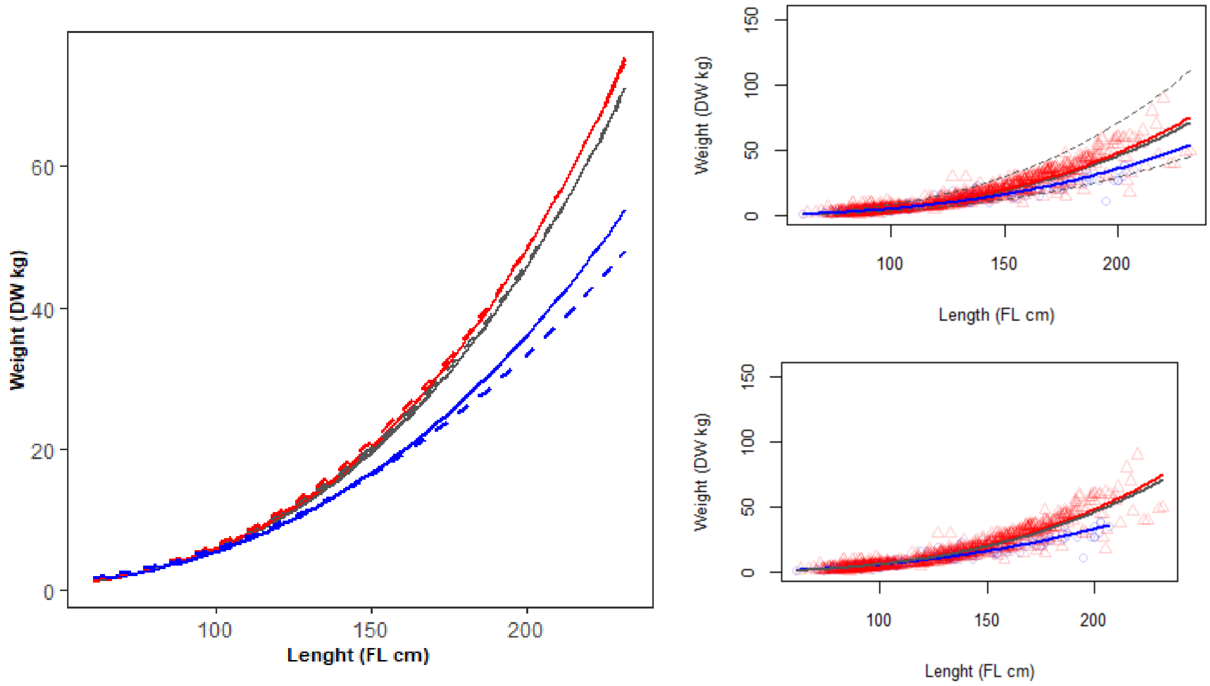


Figure 17. Length (FL cm) – dressed (DW kg) linear relationships of oceanic whitetip shark (OCS) from the Indian Ocean. Left panel: solid line=linear model, dashed line=non-linear model. Upper right panel: linear model per sex + 95% confidence intervals sex combined. Bottom right panel: non-linear model per sex. Colors: blue=males, red=females, black=females+males.

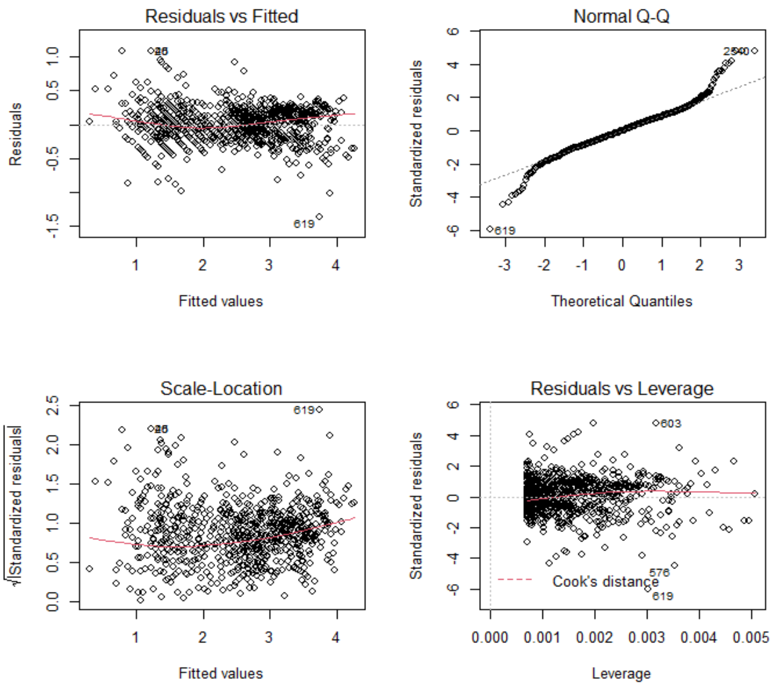


Figure 18. Diagnosis of the residuals of the size (FL cm)–dressed weight (DW kg) linear relationship of oceanic whitetip shark (OCS) from Indian Ocean stock. Residuals *vs.* fitted values, qq-plot and residuals *vs.* leverage.

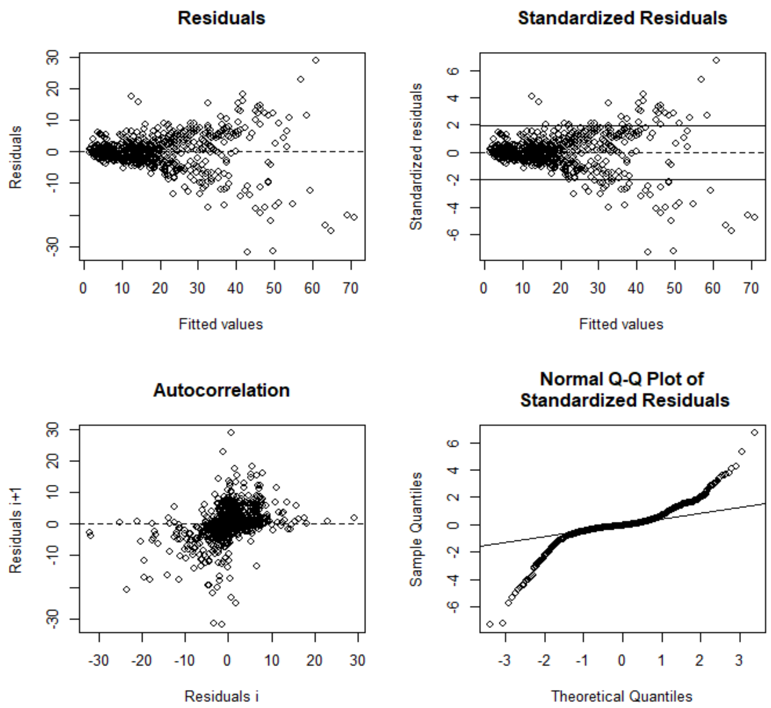


Figure 19. Diagnosis of the residuals of the size (FL cm)–dressed weight (DW kg) non linear relationship of oceanic whitetip shark (OCS) from Indian Ocean stock.

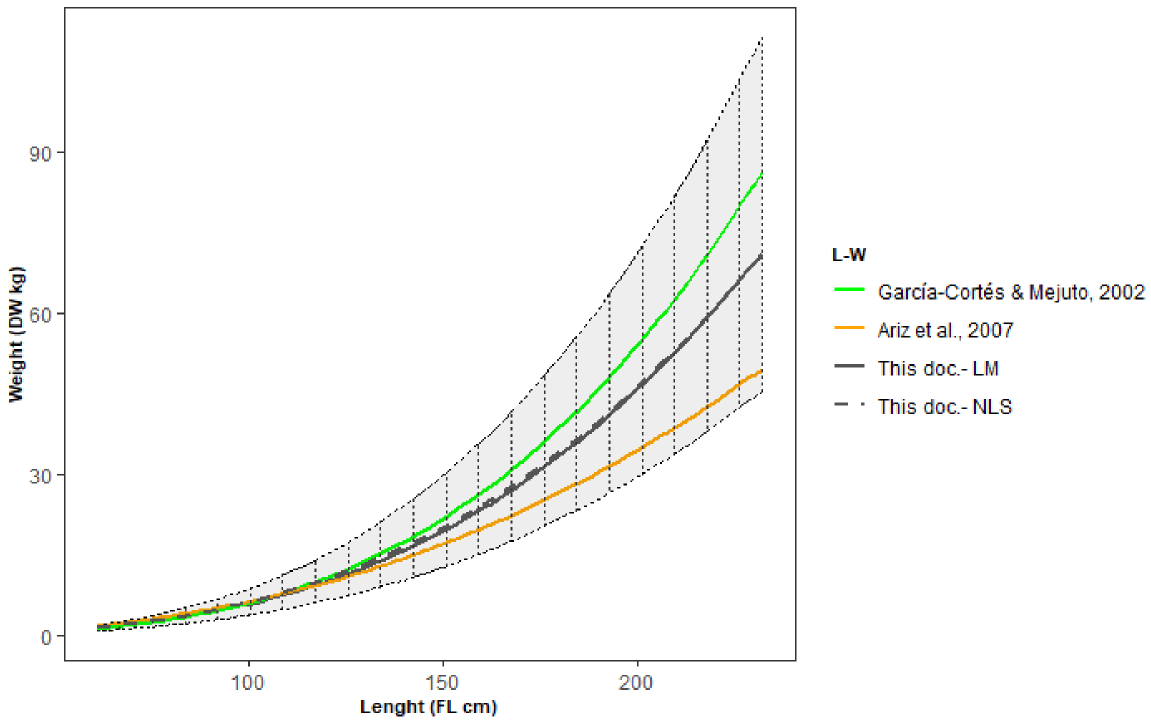


Figure 20. Fitting of DW~FL published equations for OCS *versus* the equations obtained by the present analyzes. Gray shading=95%CI LM analysis of this document.