Estimating total mortality rates and calculating overfishing limits from length observations for six U.S. Caribbean stocks

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1. Introduction

The mean length-based estimator of Gedamke and Hoenig (2006) is a non-equilibrium extension of the Beverton-Holt mean length mortality estimator used to estimate total instantaneous mortality rates Z. Gedamke and Hoenig (2006) derived the transitional behavior of the population mean length following a change in Z and then generalized the derivation to include multiple changes in total mortality. From a time series of mean length data, total mortality rates are estimated in blocks of time as well as the years in which the mortality changed. The model uses a likelihood approach to obtain parameters that maximize goodness of fit to the mean length data. The mean length estimator assumes:

1. Recruitment is constant over time.
2. Growth is deterministic following a von Bertalanffy growth equation and is time-invariant.
3. Selectivity is knife-edge above the length of full selectivity L_c and is time-invariant.

The mean length estimator requires an external estimate of von Bertalanffy growth parameters L_∞ and K and a time series of length measurements for the stock. First, the length of full selectivity L_c is obtained from the data. Typically, the L_c is selected to be the peak (mode) of the length frequency histogram of data combined for all years in the time series and the annual mean lengths of animals larger than length L_c is calculated. Annual length frequency histograms should also be examined to explore trends in the mode of the histogram over time, which would coincide with a change in selectivity or recruitment. A sensitivity analysis should also be performed in which several values of L_c are chosen and the mean lengths re-calculated for each alternative value of L_c. This allows for a test of the constancy of mortality rate over the size range assumed to be fully recruited. For increasing values of L_c, an increasing trend in the estimates of mortality may suggest dome-shaped selectivity, while no trend in the estimates would indicate that selectivity is flat-topped.

To estimate historical mortality rates, the number of changes in mortality is first specified by the user. The model is fitted multiple times with increasing complexity (more time blocks) until the increase in goodness of fit is no longer statistically significant with increasing complexity or until trends in residuals are removed. In practice, AIC is used to select the best model considering both goodness of fit and model parsimony (Burnham and Anderson 2002).

For a single stock, length data from several fleets or gears may be available, in which case the data from the best-sampled or most abundant gear should be used to prevent conflation of differing selectivity patterns with stock status.

The estimates of total mortality from the mean length estimator can be used to calculate an overfishing limit (OFL) (Bryan et al. in progress). The most recent fishing mortality rate F_{recent} in the most recent years of the time series is derived as the difference of the total mortality and an external estimate of the natural mortality rate *M*. This benchmark fishing mortality rate can be compared to a reference point $F_{reference}$. Based on the ratio of the $F_{reference}$ and F_{recent}, the management procedure adjusts recent catch C_{recent} concurrent with F_{recent} to derive an overfishing limit:

$$OFL = \frac{F_{reference}}{F_{recent}} C_{recent} \quad . \qquad (1)$$

High instantaneous fishing mortality rates should be converted to annual exploitation rates (as a ratio of the total population fished) to calculate the OFL:

$$u = 1 - \exp(-F) \quad . \qquad (2)$$

2. Application to U.S. Caribbean species

2.1. Mean length estimator

The mean length estimator was used to estimate total mortality rates for six U.S. Caribbean stocks: yellowtail snapper and hogfish in Puerto Rico (PR), queen triggerfish and spiny lobster in St. Thomas/St. John (STT), and spiny lobster and stoplight parrotfish in St. Croix (STX). Length observations were obtained from the Trip Interview Program (TIP) of the Southeast Fisheries Science Center. A summary of the data and gear aggregations is available in Bryan (2015). Life history parameters for the six stocks were obtained from Adams (2015). The modal length from length histograms of all observations was used to select L_c for the mean length estimator (Figure 1).

The mean lengths of animals above length L_c were calculated, which necessitated discarding of data of lengths below L_c. Sample sizes for the data used to calculate mean lengths are reported in Table 1. Annual length frequency figures are available in Bryan (2015). From these annual length frequency plots, the annual modal length was also calculated to detect possible changes in selectivity over time (Figure 2). Annual length frequency plots for St. Thomas/St. John spiny lobster from the trap gear and St. Croix spiny lobster from the dive/by hand/spear gear are presented in Figure 3 and Figure 4, respectively. Total mortality rates were estimated assuming up to 3 changes in mortality occurred in the time series. AIC was used to select the best fit model, with the more complex model (more changes in mortality) selected if the reduction in AIC was greater than 4 units. Sensitivity runs using alternate choices for L_c were also used (Tables 2-7). Annual mean lengths > L_c were re-calculated and the model fit and selection was repeated for each sensitivity run.

2.1.1. Puerto Rico yellowtail snapper

A total of 76,574 observations of yellowtail snapper were available from the handline gear in Puerto Rico from 1983-2013. From all records in this time period, the modal length was 280 mm. However, there appeared to be an increase in the modal length after the year 2000 suggesting a change in selectivity around this time (Figure 2a).

Since there appeared to be no trend in the modal length after 2000, the L_c was selected from the modal length from observations sampled after 2000. Thus, estimated mortality rates from the mean length estimator are assumed to be conditional on the more recent selectivity pattern. Using this criterion, the modal length was still 280 mm, which was chosen as the L_c. Total mortality was estimated to be 0.56 during 1983 - 1992, decreased to 0.26 during 1993-2004, and subsequently increased to 0.48 since 2004 (Figure 5). The estimates did not appear to be very sensitive to L_c, although there was a noticeable decrease most recent estimate of Z when a very high L_c was chosen (Table 2).

2.1.2. Puerto Rico hogfish

A total of 4,163 observations of hogfish were available from the diving/by hand/spear gear in Puerto Rico from 1983-2013. From all records in this time period, the modal length was 280 mm, which was chosen as the L_c. Total mortality was estimated to be 0.36 during 1983 - 1992, increased to 0.56 during 1993-2000, and subsequently decreased to 0.34 since 2001 (Figure 6). The estimates of Z were not particularly sensitive to the choice of L_c (Table 3).

2.1.3. St. Thomas/St. John queen triggerfish

A total of 8,051 observations of queen triggerfish were available from the trap fishery in St. Thomas/St. John from 1983-2013. The modal length was 320 mm, which was chosen as the L_c. The mean length estimator suggested equilibrium mortality during 1983-2013, i.e. no changes in mortality (Figure 7). Total mortality was estimated to be 1.34 during this period, although there is a trend in the estimated mortality depending on the choice of L_c, with higher mortality estimated when a larger L_c is used (Table 4).

2.1.4. St. Thomas/St. John spiny lobster

A total of 10,384 observations of spiny lobster were available from the trap fishery in St. Thomas/St. John from 1980-2013 (Figure 3). There were no length observations for the years 1982, 1989-1991, 1997- 2001, and 2007. Sample sizes were high prior to 1989, then declined before increasing after 2002. The modal length was 100 mm, which was chosen as the L_c. The mean length estimator suggested one change in mortality. Total mortality was estimated to be 0.59 prior to 1986 and increased to 0.98 afterwards (Figure 8). There is a slight trend in the estimated mortality depending on the choice of L_c, although the estimates are similar when the chosen L_c is 100 mm and 110 mm (Table 5).

2.1.5. St. Croix spiny lobster

A total of 6,674 observations of spiny lobster were available from the diving/by hand/spear fishery in St. Croix from 1981-2013. There are no data for 1986, 1988-1990, and 2011-2013 (Figure 4). Sample sizes increased in the 1990s and 2000s, with a declining trend since 2008. The modal length was 90 mm, which was chosen as the L_c. The mean length estimator suggested that one increase in total mortality occurred and there appears to be a decrease in the mean length over time. Total mortality was estimated to be 0.35 prior to 1979 and increased to 1.11 afterwards (Figure 9). The model estimated a mortality rate that occurred prior to 1980 to explain the decreasing trend in mean length in the initial years of the time series. Since there are no data prior to 1980, there is high uncertainty in this estimate. However, the relative stability in the mean length after the mid-1980s provided stability in the model to estimate the most recent total mortality rate. There is a trend in the estimated mortality depending on the choice of L_c, with higher mortality estimated when a larger L_c is used (Table 6).

2.1.6. St. Croix stoplight parrotfish

A total of 2,605 observations of stoplight parrotfish were available from the diving/by hand/spear fishery in St. Croix. Only 10 intermittent years of length observations were available starting in 1996. The modal length was 270 mm, which was chosen as the L_c. There was not enough information to detect a change in total mortality. The equilibrium total mortality form 1996 – 2013 was estimated to be 2.31 during this period (Figure 10). There is a trend in the estimated mortality depending on the choice of L_c, with higher mortality estimated when a larger L_c is used (Table 7).

2.2. Calculating OFLs

OFLs were calculated for the six stocks using Equation 1 using two reference points, $F_{0.1}$ and $F_{SPR\%}$, as proxies for $F_{reference}$. From a yield-per-recruit (YPR) analysis, $F_{0.1}$ is the fishing mortality rate at which the slope of the YPR curve is 10% of that at the origin. From a spawning-potential-ratio (SPR) analysis, $F_{SPR\%}$ is the fishing mortality rate that reduces the spawning biomass per recruit to a pre-specified percentage of that from unfished conditions. $F_{0.1}$ is generally used if there are concerns with growth overfishing while $F_{SPR\%}$ is used to consider recruitment overfishing (SEDAR 2014). For both, weight-at-age information for the stock is required, while SPR also requires maturity information. The YPR and SPR formulation from SEDAR (2014) was used for the analyses for this assessment. For the YPR and SPR analyses, knife-edge selectivity above length L_c. Maturity was also assumed to be knife-edge for the SPR analysis. A spawning-potential-ratio of 30% (i.e. $F_{SPR=30\%}$) was considered for all stocks.

The benchmark fishing mortality rates F_{recent} were derived as the difference of the most recent total mortality rates from the mean length estimator and external estimates of the natural mortality rate *M*. For the four St. Thomas/St. John and St. Croix stocks, exploitation rates *u* were used in lieu of high instantaneous fishing mortality rates. Recent catch was calculated as the mean of total catch corresponding to the time interval of the most recent mortality rate estimated by the mean length estimator. For example, for Puerto Rico yellowtail snapper, the change to the latest mortality rate was estimated to occur at 2004.5. Thus, mean catch since 2005 was used as C_{recent} in Equation 1.

For all stocks, $F_{0.1}$ was lower than $F_{30\%}$ (Table 8). For St. Thomas/St. John spiny lobster, the spawning potential ratio did not reach 30% from that at unfished conditions for any practical fishing mortality rate. Thus, a spawning potential ratio of 40% was considered for this stock. For all stocks, the benchmark F_{recent} was above the reference $F_{0.1}$ and the respective $OFL_{F0.1}$ were adjusted downward from the mean catch. Using $F_{SPR\%}$, the $OFL_{FSPR\%}$ was a much smaller reduction from mean catch compared to $OFL_{F0.1}$ for Puerto Rico hogfish, St. Thomas/St. John queen triggerfish, and St. Croix spiny lobster. For Puerto Rico yellowtail snapper and St. Thomas/St. John spiny lobster, the $OFL_{FSPR\%}$ control rule increased the overfishing limit above the mean catch. For St. Croix stoplight parrotfish, both control rules significantly reduced the mean catch to obtain the OFL.

In addition to the point estimates, a distribution of OFLs was calculated incorporating uncertainty in life history parameters and catch data with the DLMtool package (Carruthers et al. 2014). 500 simulations were performed using $F_{0.1}$ and $F_{SPR\%}$ ($F_{40\%}$ for St. Thomas/St. John spiny lobster, $F_{30\%}$ for all others) as reference points using assuming lognormal error in natural mortality, growth, maturity, and catch. OFLs were positively skewed, with those obtained from $F_{SPR\%}$ as the reference point larger than those from $F_{0.1}$ (Figure 11). The point estimates for the OFLs were generally close to the median, but for St. Croix stoplight parrotfish using both $F_{0.1}$ and $F_{30\%}$, where both point estimates were significantly larger than the median.

3. Discussion

In general, $F_{SPR\%}$ produced OFLs with smaller deviations from mean catch compared to $F_{0.1}$. The benchmark mortality estimates for Puerto Rico yellowtail snapper and hogfish from the mean length estimator appear consistent with the stocks' respective life histories. These estimates were insensitive across the range of values for L_c for the mean length estimator. Using $F_{0.1}$, a large reduction in the mean catch was indicated for the OFL for both stocks. Using $F_{30\%}$, the reduction was slight for hogfish while there was a large increase of the mean catch for the OFL for yellowtail snapper.

For St. Thomas/St. John and St. Croix spiny lobster, the estimates of total mortality are somewhat high compared to the stocks' life histories. Using $F_{0.1}$, a large reduction in the mean catch was indicated for the OFL for both stocks. Using $F_{30\%}$, the reduction was still substantial for St. Croix. Due to the larger full selectivity length L_c for the St. Thomas/St. John stock (100 mm vs. 90 mm), $F_{30\%}$ could not be obtained. $F_{40\%}$ was used instead as the SPR proxy, which still provided for a larger OFL relative to mean catch.

For St. Thomas/St. John queen triggerfish and St. Croix stoplight parrotfish, the estimates of total mortality were very high. For queen triggerfish, a large reduction in the mean catch was indicated for the OFL using $F_{0.1}$ while the reduction was more modest using $F_{30\%}$. St. Croix stoplight parrotfish was a noticeable outlier for the high estimates of total mortality and deviations in the point estimate and the distribution of OFL. In addition to high exploitation, the high estimated total mortality rate could also arise from a positive-biased estimate of the von Bertalanffy L_∞ and/or severe dome-shaped selectivity. Both point estimate OFLs indicated a large reduction in catch, but there is more uncertainty as these estimates were not close to the median from the simulations.

4. Acknowledgements

I would like to thank SEFSC and Clay Porch for travel support; Larry Beerkircher for assistance with the data; Nancie Cummings, Skyler Sagarese, Tom Carruthers for assistance with the DLMtool package; and Meaghan Bryan for assistance with computer code and review.

5. References

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6. Tables

Table 1. Annual sample sizes of length observations greater than length L_c used in mean length estimator.

Year	Yellowtail snapper (PR) $L_c = 280$ mm	Hogfish (PR) $L_c = 280$ mm	Queen trigger-fish (STT) $L_c = 320$ mm	Spiny lobster (STT) $L_c = 100$ mm	Spiny lobster (STX) $L_c = 90$ mm	Stoplight parrot-fish (STX) $L_c = 270$ mm
1980	0	0	0	164	0	0
1981	0	0	0	456	135	0
1982	0	0	0	0	72	0
1983	19	21	5	43	88	0
1984	376	44	332	619	126	0
1985	658	60	299	646	6	0
1986	225	16	187	239	0	0
1987	34	50	50	356	9	0
1988	328	82	0	530	0	0
1989	141	153	0	0	0	0
1990	562	148	0	0	0	0
1991	4420	149	0	0	242	0
1992	3601	108	0	156	438	0
1993	2370	68	111	137	326	0
1994	1695	15	63	53	283	0
1995	1699	43	43	29	92	0
1996	183	30	13	87	29	4
1997	256	38	0	0	219	0
1998	1132	61	0	0	283	64
1999	2023	135	0	0	272	0
2000	2498	158	0	0	201	0
2001	1285	237	0	0	295	0
2002	2341	103	133	281	570	56
2003	3156	112	43	337	557	60
2004	1571	87	15	117	412	37
2005	1647	93	86	128	435	0
2006	1962	103	109	566	360	171
2007	2441	64	0	0	514	338
2008	1633	45	11	72	158	363
2009	2013	244	348	585	75	488
2010	1699	205	727	768	109	1
2011	520	297	431	494	0	0
2012	668	222	81	369	0	0
2013	266	116	0	225	0	0

Table 2. Sensitivity analysis to L_c for estimated mortality history for Puerto Rico yellowtail snapper. Bold indicates L_c chosen from modal length of length frequency histogram.

L_c	Z_1	Change Year 1	Z_2	Change Year 2	Z_3
260	0.55	1993.2	0.24	2005.3	0.48
280	**0.56**	**1992.8**	**0.26**	**2004.5**	**0.48**
300	0.54	1992.8	0.24	2004.5	0.41
320	0.48	1992.5	0.19	1996.6	0.35

Table 3. Sensitivity analysis to L_c for estimated mortality history for Puerto Rico hogfish. Bold indicates L_c chosen from modal length of length frequency histogram.

L_c	Z_1	Change Year 1	Z_2	Change Year 2	Z_3
260	0.33	1989.7	0.51	2001.7	0.32
280	**0.36**	**1992.8**	**0.56**	**2000.7**	**0.34**
300	0.36	1993.6	0.57	2000.3	0.36
320	0.37	1995.0	0.59	1999.9	0.36

Table 4. Sensitivity analysis to L_c for estimated mortality history for St. Thomas/St. John queen triggerfish. Bold indicates L_c chosen from modal length of length frequency histogram.

L_c	Z
300	1.15
320	**1.34**
340	1.53
360	1.70

Table 5. Sensitivity analysis to L_c for estimated mortality history for St. Thomas/St. John spiny lobster. Bold indicates L_c chosen from modal length of length frequency histogram.

L_c	Z_1	Change Year	Z_2
90	0.51	1985.7	0.76
100	**0.59**	**1986.0**	**0.98**
110	0.60	1986.3	0.94
120	0.61	1985.7	1.10

Table 6. Sensitivity analysis to L_c for estimated mortality history for St. Croix spiny lobster. Bold indicates L_c chosen from modal length of length frequency histogram.

L_c	Z_1	**Change Year**	Z_2
80	0.35	1979.1	0.73
90	**0.35**	**1979.6**	**1.11**
100	0.74	1989.7	1.38
110	0.90	1990.2	1.69

Table 7. Sensitivity analysis to L_c for estimated mortality history for St. Croix stoplight parrotfish. Bold indicates L_c chosen from modal length of length frequency histogram.

L_c	Z
250	1.88
270	**2.31**
290	2.64

Table 8. Derived overfishing limits using the life history point estimates, mean length mortality estimator, per-recruit analyses, and recent catch.

Stock	Time Period for Z_{recent}	Estimated Z_{recent}	M	F_{recent}	$F_{0.1}$	$F_{SPR\%}$*	Mean catch (pounds)	Time Period of catch	OFL $F_{0.1}$	OFL $F_{SPR\%}$*
Yellowtail snapper (PR)	2005 – 2013	0.48	0.19	0.29	0.21	0.44	278,060	2005 - 2014	201,354	421,884
Hogfish (PR)	2001 – 2013	0.34	0.16	0.18	0.11	0.17	74,931	2001 - 2014	45,791	70,768
Queen triggerfish (STT)	1983 – 2013	1.34	0.26	1.08 u=0.66	0.29 u=0.25	0.90 u=0.59	69,274	1998 - 2014	26,406	62,249
Spiny lobster (STT)	1986 – 2013	0.98	0.35	0.63 u=0.47	0.39 u=0.32	0.83 u=0.56	88,117	1986 - 2014	60,882	106,318
Spiny lobster (STX)	1980 – 2013	1.02	0.35	0.76 u=0.53	0.30 u=0.26	0.68 u=0.49	80,136	1980 – 2014	29,279	55,736
Stoplight parrot-fish (STX)	1996 - 2013	2.31	0.30	2.01 u=0.87	0.23 u=0.21	0.38 u=0.32	90,089	1996 – 2014	21,374	32,887

* A spawning potential ratio (SPR) of 40% was used for St. Thomas/St. John spiny lobster and 30% for all other stocks.

7. Figures

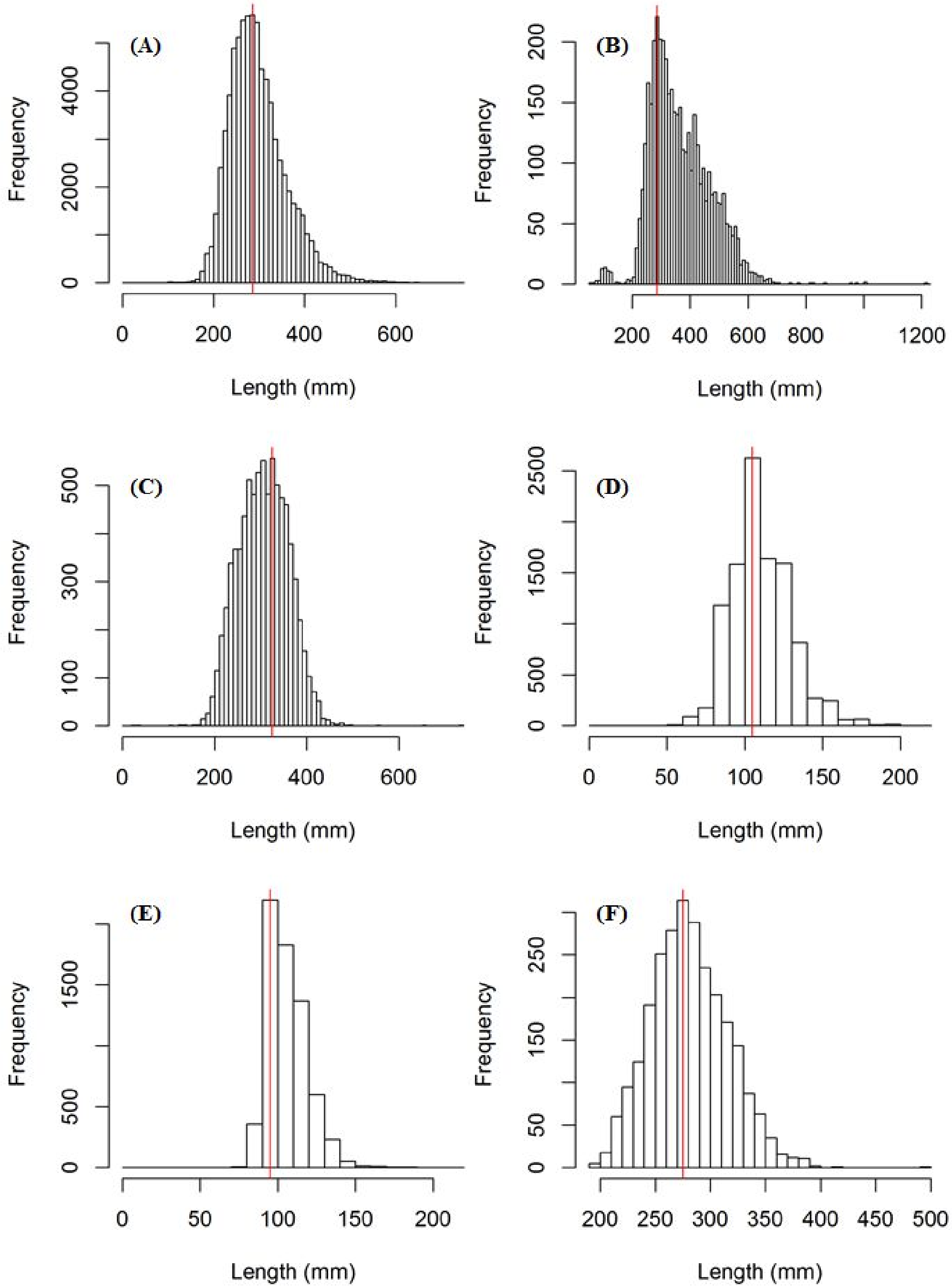

Figure 1. Length frequency histograms for (a) Puerto Rico yellowtail snapper from handline gear, (b) Puerto Rico hogfish from diving/by hand/spear gear, (c) St. Thomas/St. John queen triggerfish from trap gear, (d) St. Thomas/St. John spiny lobster from trap gear, (e) St. Croix spiny lobster from diving/by hand/spear gear, and (f) St. Croix stoplight parrotfish from diving/by hand/spear gear. Vertical red lines indicate the modal length of the histogram. All length bins are 10 mm.

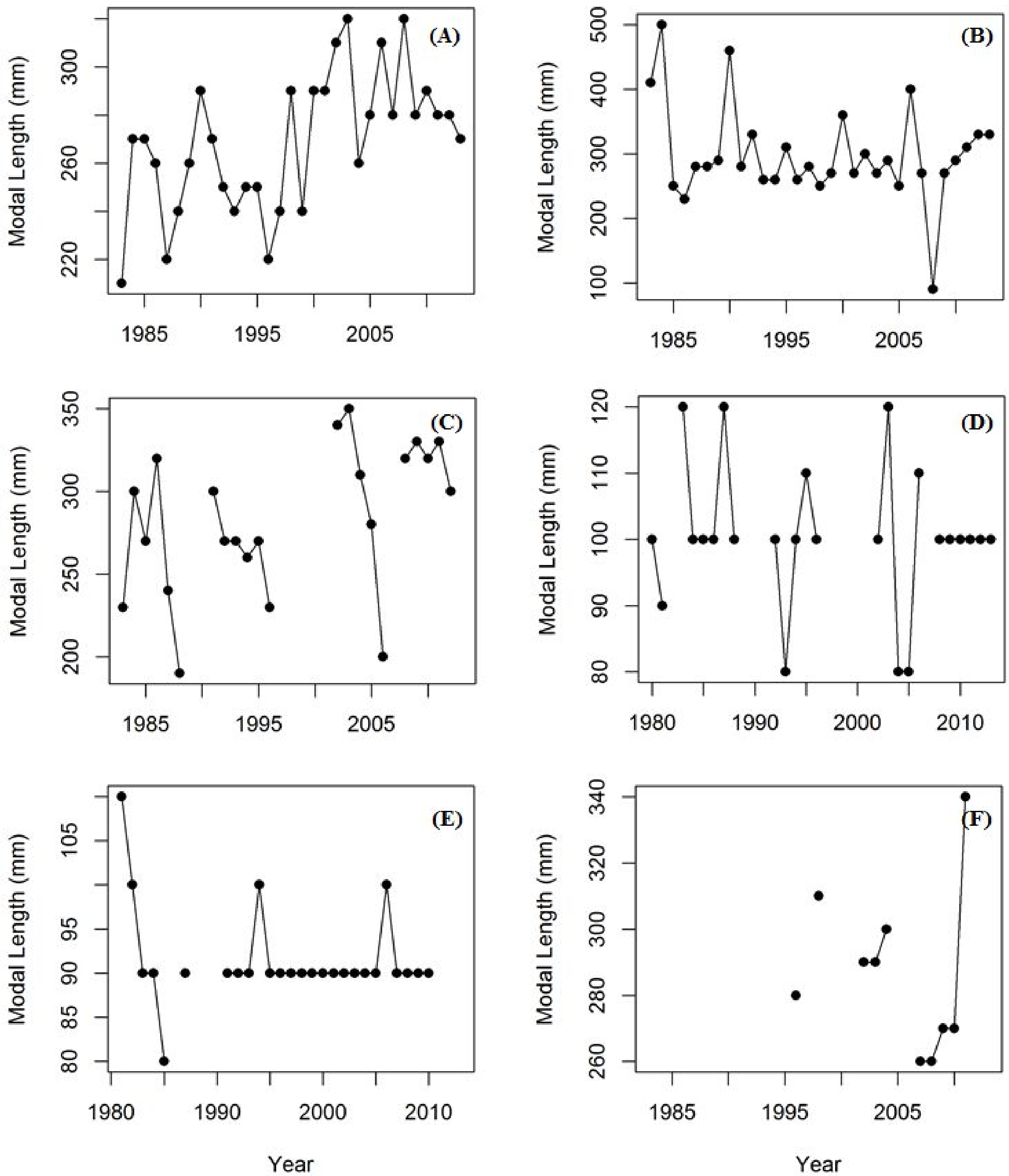

Figure 2. Annual modal lengths for (a) Puerto Rico yellowtail snapper from handline gear, (b) Puerto Rico hogfish from diving/by hand/spear gear, (c) St. Thomas/St. John queen triggerfish from trap gear, (d) St. Thomas/St. John spiny lobster from trap gear, (e) St. Croix spiny lobster from trap gear, and (f) St. Croix stoplight parrotfish from diving/by hand/spear gear.

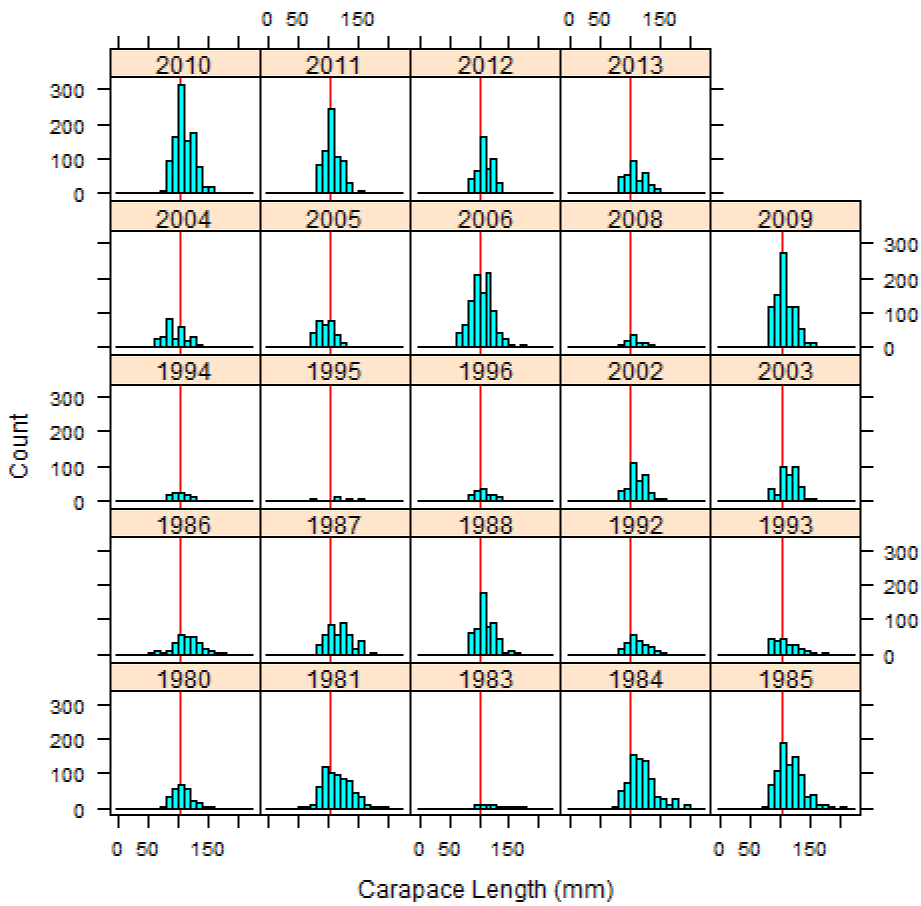

Figure 3. Annual length frequency histograms for St. Thomas/St. John spiny lobster from trap gear. Length bins are 10 mm.

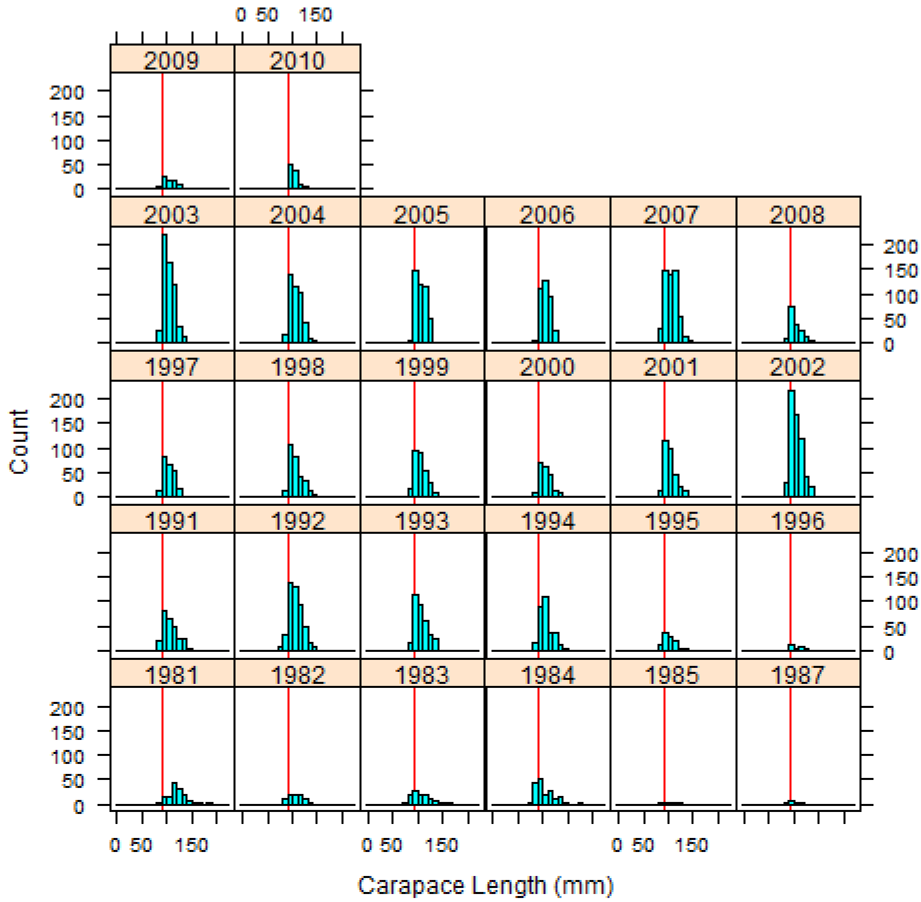

Figure 4. Annual length frequency histograms for St. Croix spiny lobster from dive/by hand/spear gear. Length bins are 10 mm.

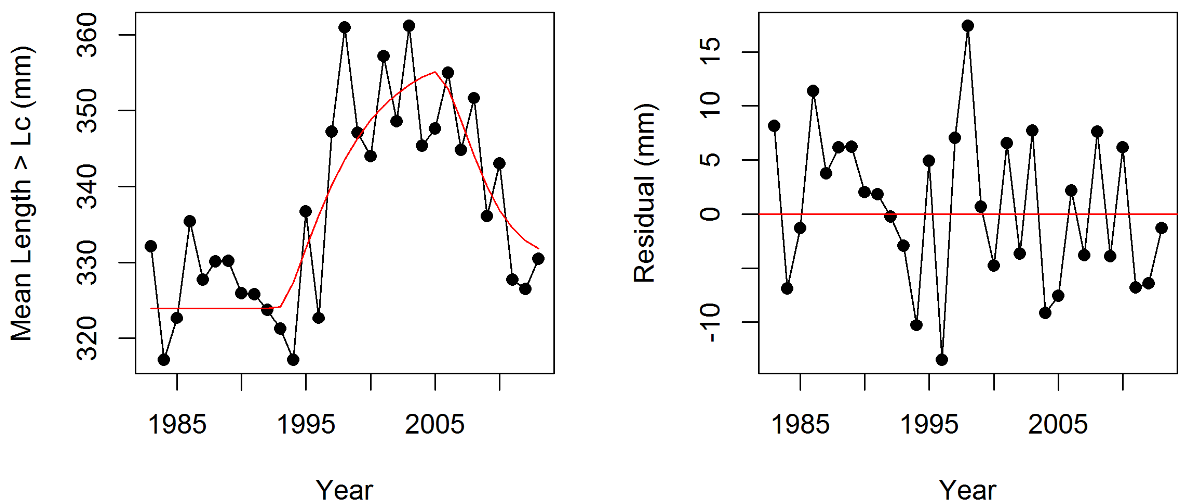

Figure 5. Observed (black) and predicted (red) mean lengths [left] and residuals [right] for Puerto Rico yellowtail snapper from handline gear, using L_c of 280 mm.

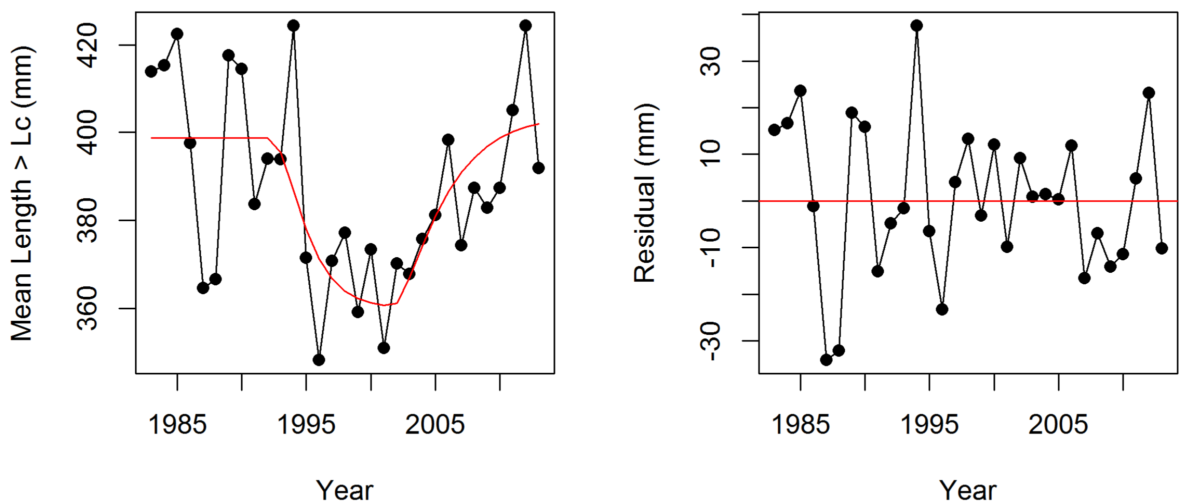

Figure 6. Observed (black) and predicted (red) mean lengths [left] and residuals [right] for Puerto Rico hogfish from diving/by hand/spear gear, using L_c of 280 mm.

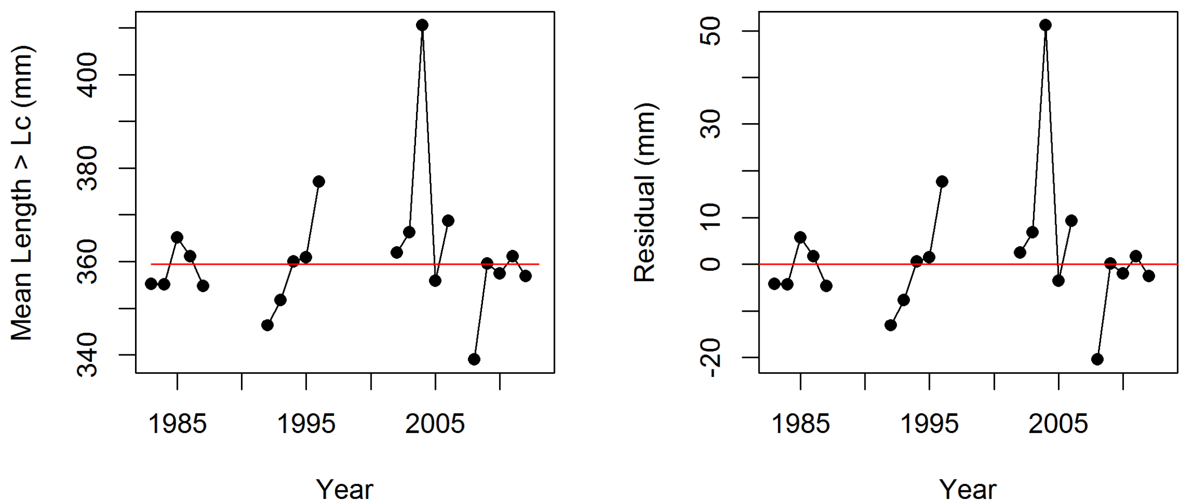

Figure 7. Observed (black) and predicted (red) mean lengths [left] and residuals [right] for St. Thomas/St. John queen triggerfish from trap gear, using L_c of 320 mm.

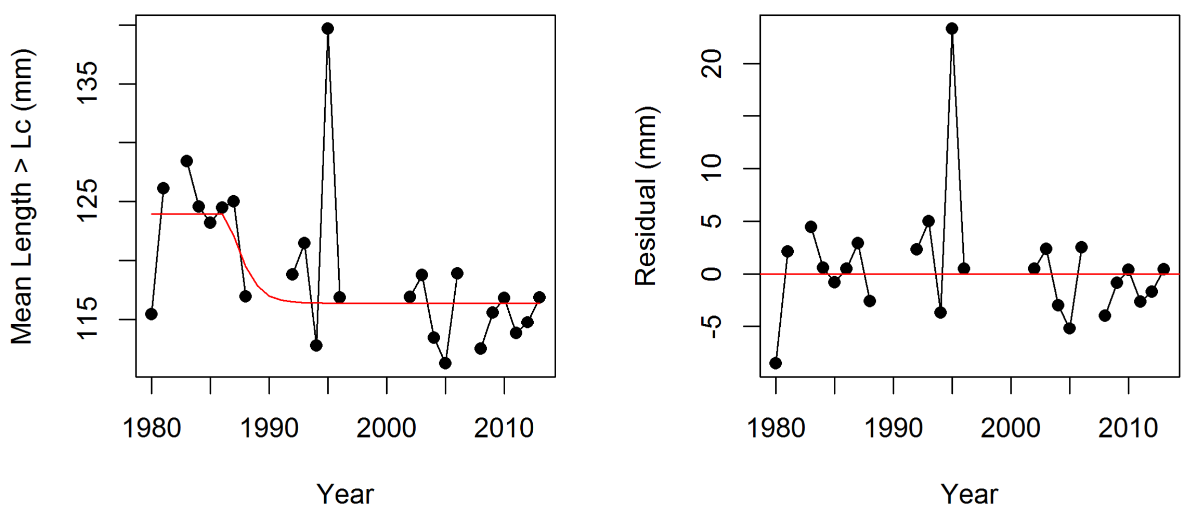

Figure 8. Observed (black) and predicted (red) mean lengths [left] and residuals [right] for St. Thomas/St. John spiny lobster from trap gear, using L_c of 100 mm.

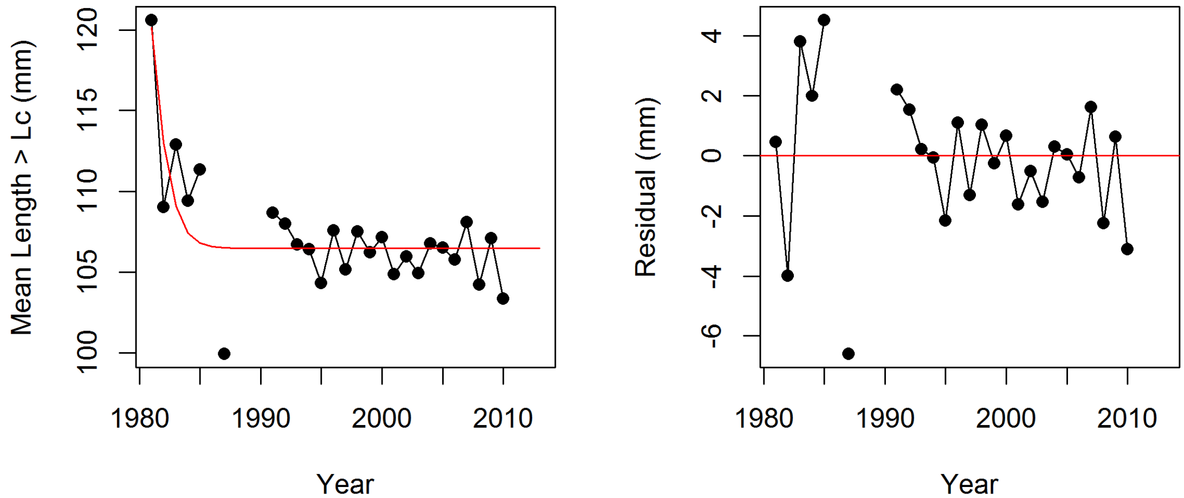

Figure 9. Observed (black) and predicted (red) mean lengths [left] and residuals [right] for St. Croix spiny lobster from diving/by hand/spear gear, using L_c of 90 mm.

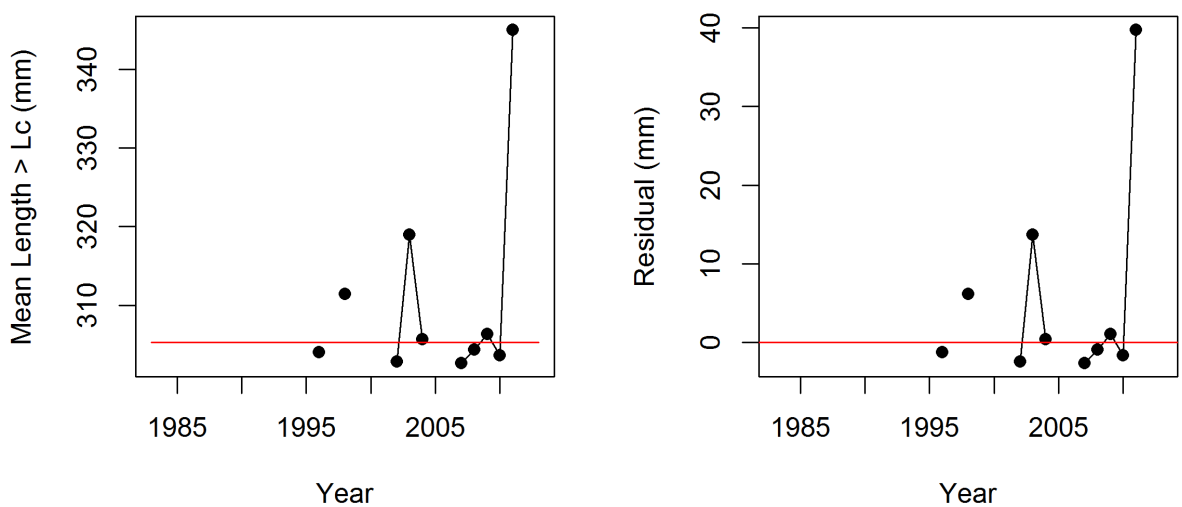

Figure 10. Observed (black) and predicted (red) mean lengths [left] and residuals [right] for St. Croix stoplight parrotfish from diving/by hand/spear gear, using L_c of 270 mm.

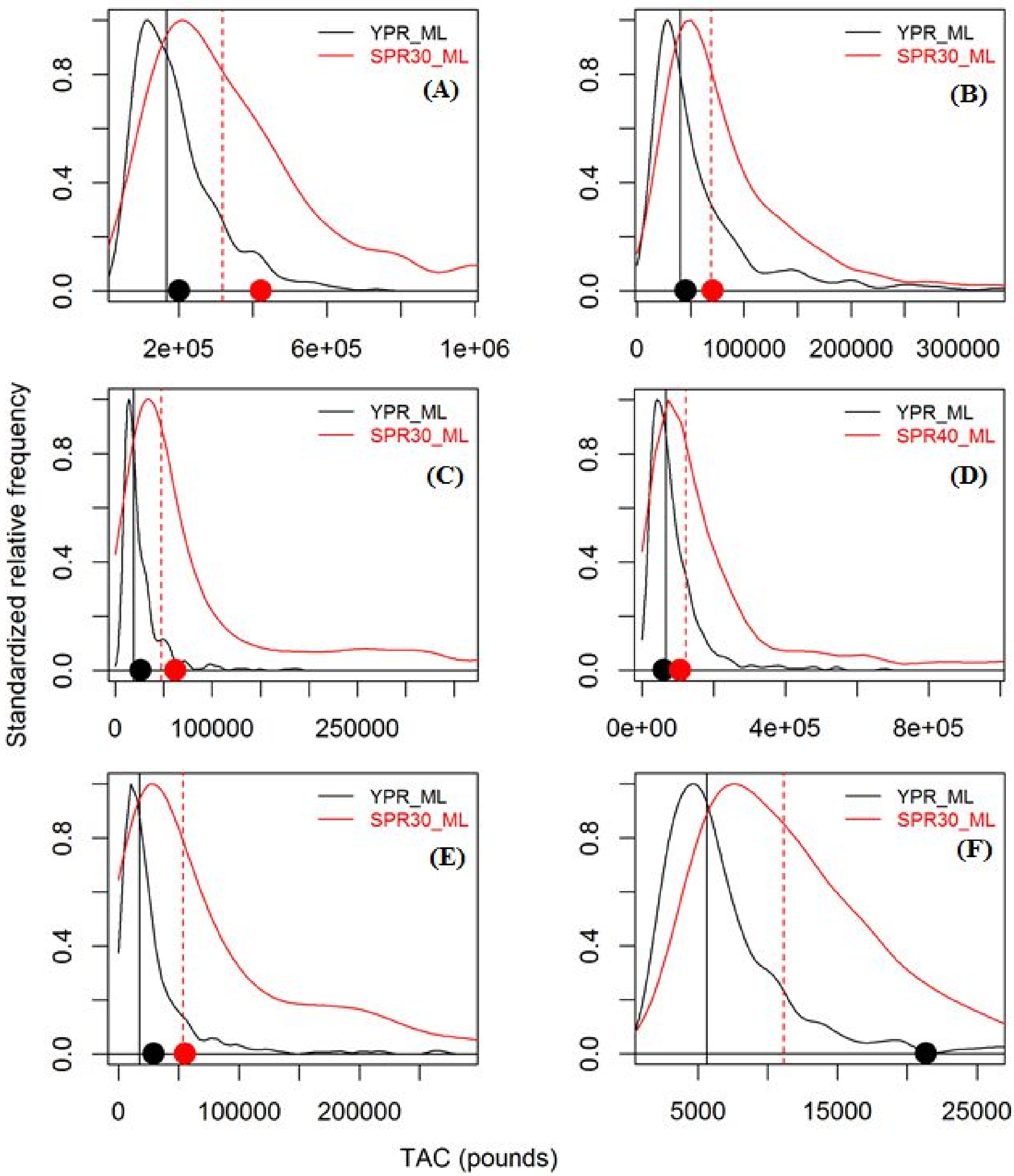

Figure 11. Distribution of OFL estimates from DLMtool using $F_{0.1}$ (YPR_ML, black) and $F_{SPR\%}$ (SPR30_ML or SPR40_ML, red) for (a) Puerto Rico yellowtail snapper, (b) Puerto Rico hogfish, (c) St. Thomas/St. John queen triggerfish, (d) St. Thomas/St. John spiny lobster (which used $F_{40\%}$), (e) St. Croix spiny lobster, and (f) St. Croix stoplight parrotfish. Vertical lines represent the median of the distribution. Black and red dots represent OFL estimate using mean catch and point estimates for life history for $F_{0.1}$ and $F_{SPR\%}$, respectively.