Feasible Bounds on Historic Butterfish Stock Size and Fishing Mortality Rates from Survey and Catch Data

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Summary

This updates some results provided by Miller and Rago (2012) based an empirical analysis of Atlantic butterfish survey and catch data to include 2012. The results provide a likely range of historic stock size and fishing mortality rates under a range of assumptions for survey catchability (0.1 and 1) and natural mortality (0.8 and 1.1). Survey data were expanded to total swept area biomasses for assumed catchabilities. For each combination of the catchabilities and natural mortality rates, historic fishing mortality and January 1 biomasses were also obtained by coupling with catch data. Results of an analytical stock assessment model (SARC 49, NEFSC 2010) comport well with the time series of *F* and biomass obtained from this method.

An examination of scenarios for biomass in 2013 based on survey and catch data in 2006–2012 suggest that overfishing is unlikely to occur in 2013 if catch is less than 17,700 mt even under the most extreme assumptions of 100% survey catchability, M = 0.8. If instead biomass in 2013 is assumed to be similar to those in 2009-2012, overfishing is unlikely for catches less than 35,100 mt. A sensitivity analysis indicates that an eight-fold increase in catches in 2012 would not have resulted in overfishing. Based on survey results, stock biomass appeared to increase by more than three-fold between 2008 and 2011, but then dropped back down to almost 2008 levels in 2012.

Introduction

Stock assessment models typically incorporate two primary sources of information: estimates of total catch (landings plus discards), and fishery-independent indices of abundance. The former quantities provide estimates of population scale, the latter quantities provide measures of trend. Total catch provides some insight into the scale of the population but without additional information it is impossible to determine if total catch is the result of a low fishing mortality rate applied to a large population or a high fishing mortality rate applied to a small population. Fishery independent stock size estimates from trawl surveys, expressed in terms of average catch per tow, approximate the true population size subject to an arbitrary scalar that reflects gear efficiency, availability, and the variability in the realization of the sampling design. Collectively these factors are called catchability and denoted as the parameter q.

Here we use the same simple approach as Miller and Rago (2012) that provides a feasible range or "envelope" of possible population sizes. Coherence between the envelope of derived stock sizes and the estimates provided by the last assessment allows us to draw some general conclusions about the relationship of catch and the probability of overfishing.

Method

Our method is the same as that provided by Miller and Rago (2012) in the section "Envelope method without the fishing mortality assumption." Let I_t represent the

observed index of biomass at time *t* and C_t represent the catch at time *t*. The estimated swept area total biomass consistent with the index is

$$B_t = \frac{I_t}{q}\frac{A}{a} \tag{1}$$

where the catchability or efficiency q, is an assumed value. The average area swept per tow is *a* and the total area of the survey is *A*. The biomass consistent with observed catch can be obtained from the Baranov catch equation as

$$B_0 = \frac{C_t}{\frac{F}{F+M}(1-e^{-(F+M)})}$$

$$B_t = B_0 e^{-(F+M)t} \tag{2}$$

where F is unknown. The second equation in Eq. 2 adjusts the biomass to the time of year when the survey occurs, thus keeping Eq. 1 and 2 consistent. Thus biomass can be written as a function of arbitrary scalars q and F.

Assessment models commonly assume that the efficiency of the survey is constant over time, but it is unlikely that fishing mortality is constant from year to year. Given assumed values of survey efficiency and natural mortality, and known annual total catch and relative biomass indices, Equation 2 can be used to obtain fishing mortality in year y numerically, and therefore the January 1 stock biomass as well. The equation to satisfy is

$$C_y = \frac{F_y}{F_y + M}\left(1 - e^{-(F_y+M)}\right)B_{0,y} \tag{3}$$

which from Equation 2 is related to the survey index I that occurs after fraction f of the year has passed,

$$B_{0,y} = B_{f,y}e^{(F_y+M)f} = \frac{I_{f,y}}{q}\frac{A}{a}e^{(F_y+M)f}. \tag{4}$$

Results

We provide the same results found in Miller and Rago (2012), but updated to include 2012. Assumed survey efficiencies are 0.1 and 1 to provide a range of biomasses implied by the survey index in a given year. The two natural mortality rates are 0.8 and 1.1. The lower values were used in the assessment model presented at SARC 49, but there was also evidence provided at that meeting that it could be greater than the assumed rate (NEFSC 2010). We specified the NEFSC fall survey to occur 0.75 (=*f*) through each year.

The results prior to 2012 are identical to Figures 4 and 5 in Miller and Rago (2012). The implied fishing mortality in 2012 is not noticeably different than others since 2003 (Fig. 2, this document). The implied January 1 biomass in 2012 is lower than others since the last assessment (2009-2011) and more similar to those in 2008 (Fig. 3).

We also explored fishing mortality rates associated with specified catches given January 1 biomasses in recent years under the assumptions that survey catchability (q) equals 1 and natural mortality (M) equals 0.8. More specifically, given the January 1 stock biomass implied by the realized catch and biomass at the time of the survey, we determined the fishing mortality over a range of assumed total catches. Our results also accounted for the uncertainty in catches (due to discards) and survey indices using a parametric bootstrap so that an estimate of probability of fishing mortality being greater than some value at a given catch can be obtained under the various assumptions. We assumed catches and indices were log-normal distributed. Letting X be the natural log of catch or survey index and CV the estimated coefficient of variation of the untransformed catch or survey index, bootstrapped values X^* were normally distributed,

$$X^* \sim N\left(X - \frac{CV^2}{2}, CV^2\right)$$

where CV^2 is a delta-method based variance of X. The subtraction of half of the variance from the mean provides a bias correction so that

$$E\left(e^{X^*}\right) = e^X.$$

Similar to Miller and Rago (2012), we used the average January 1 biomass in the recent years in a given bootstrap to determine F at the specified catches for that bootstrap. When these results are used to evaluate potential catch levels in 2013, this implies that January 1 biomass in 2013 is predicted to be similar to the mean January 1 biomass in the recent years. We performed two sets of bootstraps using catches and survey indices from 2006-2012, and just the years 2009-2012 that did not require calibration of Bigelow survey data (Tables 1 and 2). We performed these calculations for 1000 bootstrap realizations.

When survey and catch data between 2006-2012 are used with the M = 0.8 and q = 1 assumptions that provide conservative biomasses, the median of average January 1 biomasses is 61,481 mt (Figs. 4 and 5). The median fishing mortality is less than any of the proposed overfishing reference points or F=2M/3, for specified total catches less than 17,700 mt, a catch that is 8.7 times greater than the average catch (2,035 mt) in that period (Fig. 6). The catch limit of 17,700 mt is somewhat larger than the 16,300 mt found by Miller and Rago (2012, in the presentation to the SSC). The probability of fishing mortality being below $F_{40\%} \approx 2M/3$ changes from 1 to 0.2 over a relatively small range of annual total catch, 12,800 –19,600 mt (Fig. 7).

In the alternative scenario based on data between 2009-2012, the median of average January 1 biomasses is 70,856 mt (Figs. 8 and 9). Median fishing mortality is less than any of the reference points when total catch is less than 35,100 mt, which is 13.4 times greater than the average catch (2,614 mt), in that period (Fig. 10). In the alternative scenario, the probability of fishing mortality being below $F_{40\%} \approx 2M/3$ changes from 1 to 0.2 over a relatively broader range of annual total catch, 23,100 – 39,800 mt (Fig. 11).

Discussion and Conclusions

There are some important assumptions associated with the approach we used that were previously noted by Miller and Rago (2012) and they discuss implications of departures from them on the calculated *F* and biomass values. For the sake of completeness, the assumptions are summarized in Appendix 2.

The parametric bootstrap method is the same as that used to generate results provided to the SSC in the presentation at their May 2012 meeting. The analysis was carried out after the Miller and Rago (2012) report was supplied to the SSC and was intended to both account for uncertainty in the catch and index data and provide a probabilistic evaluation of fishing mortalities associated with potential catch specifications. Given the role of butterfish in the ecosystem as a prey species, the SSC determined that an $F = 2M/3$ is an appropriate target based on Patterson (1992). For $M = 0.8$, $F_{40\%}$ (0.52) from the previous assessment is approximately the same as $2M/3$ (0.54).

The results from the bootstrap analysis are different because 2012 data were included and 2005 data were omitted. The catch providing median $F = F_{40\%}$ is slightly greater than the analyses presented at the May 2012 meeting because the 2012 January 1 biomass is slightly higher than the 2005 January 1 biomass that was omitted. The alternative analysis is also different because it only includes 2009-2012 data. The catch associated with median $F = F_{40\%}$ is greater than the base analysis because the lower 2007 and 2008 January 1 biomasses are omitted. Both results show median F associated with current average catch is less than $F_{40\%} \approx 2M/3$.

Our results suggest the following:

- Current fishing mortality rates are low in absolute terms and relative to natural mortality and a suite of candidate biological reference points.
- Median stock biomass over 2009-2012 is 70,856 mt with a 95% CI of 53,472 to 95,546 mt.
- Irrespective of the time period used (i.e., 2006-12 vs. 2009-2012) butterfish catches less than 11,000 mt would have almost no chance of exceeding a fishing mortality threshold of $2M/3$.

References

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Miller, T., and P. Rago. 2012. Empirical exploration of feasible bounds on butterfish stock size and fishing mortality rates, 1975-2011. Report to the Mid-Atlantic Fishery Management Council Scientific and Statistical Committee. 14 pp.

NEFSC. 2010. 49th Northeast Regional Stock AssessmentWorkshop (49th SAW) Assessment Report. NEFSC Ref. Doc. 10-03.

Patterson, K. 1992. Fisheries for small pelagic species: an empirical approach to management targets. Reviews in Fish and Fisheries 2:321-338.

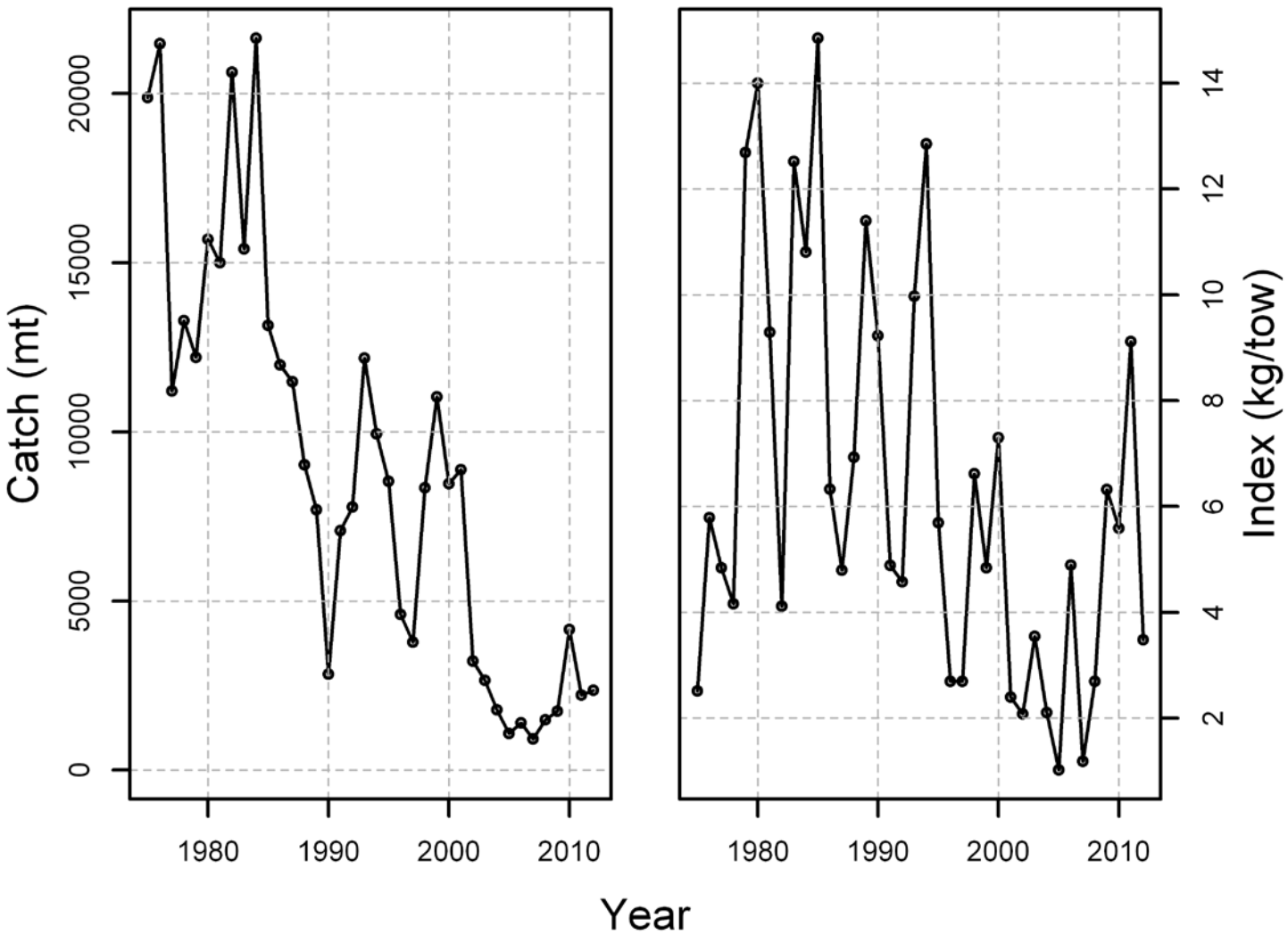

Figure 1. Annual total catches and fall NEFSC biomass indices for Atlantic butterfish.

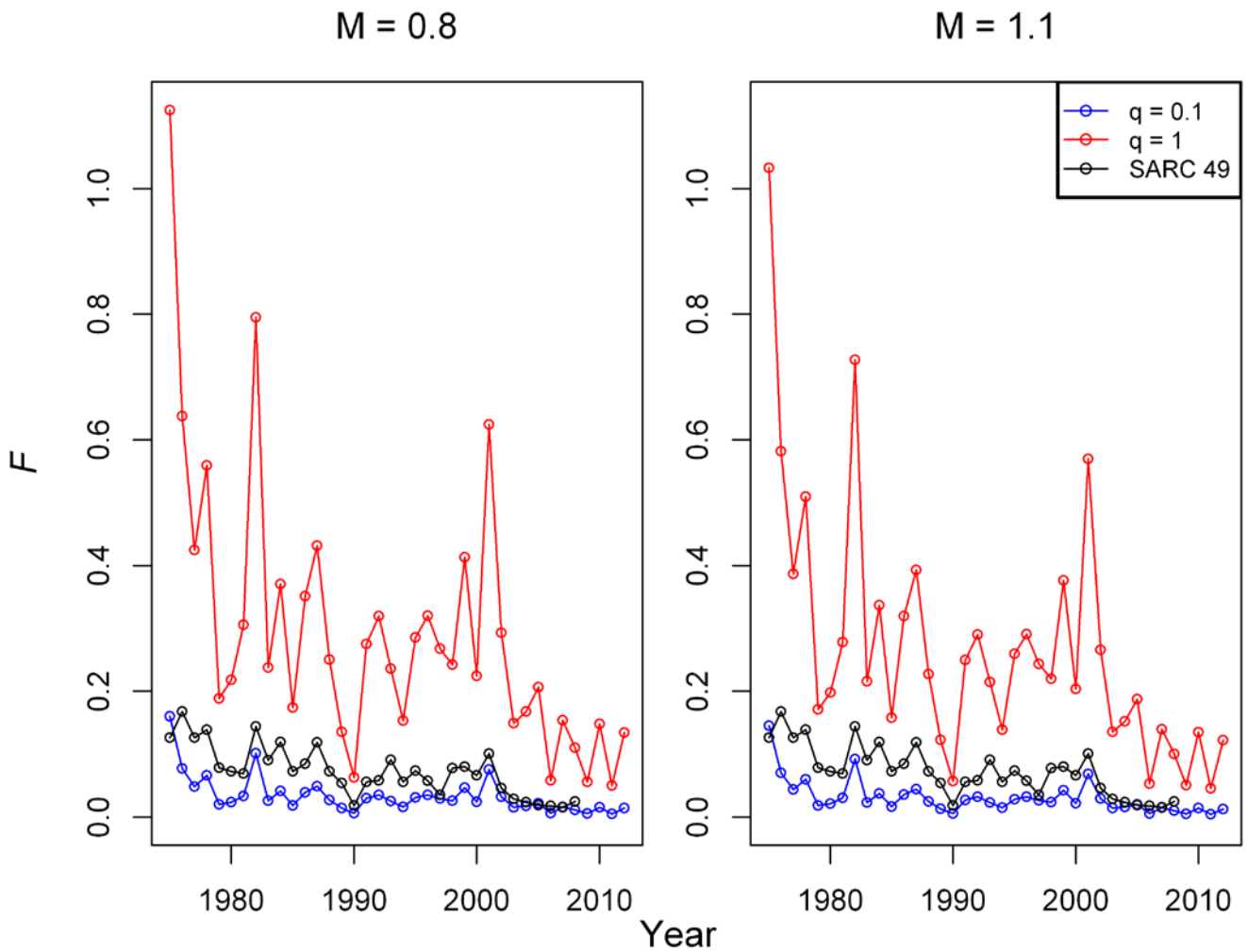

Figure 2. Implied annual fishing mortality rates under two different survey efficiency and natural mortality assumptions and the fishing mortality rate estimates from SARC 49 (NEFSC 2010). See Equation 3.

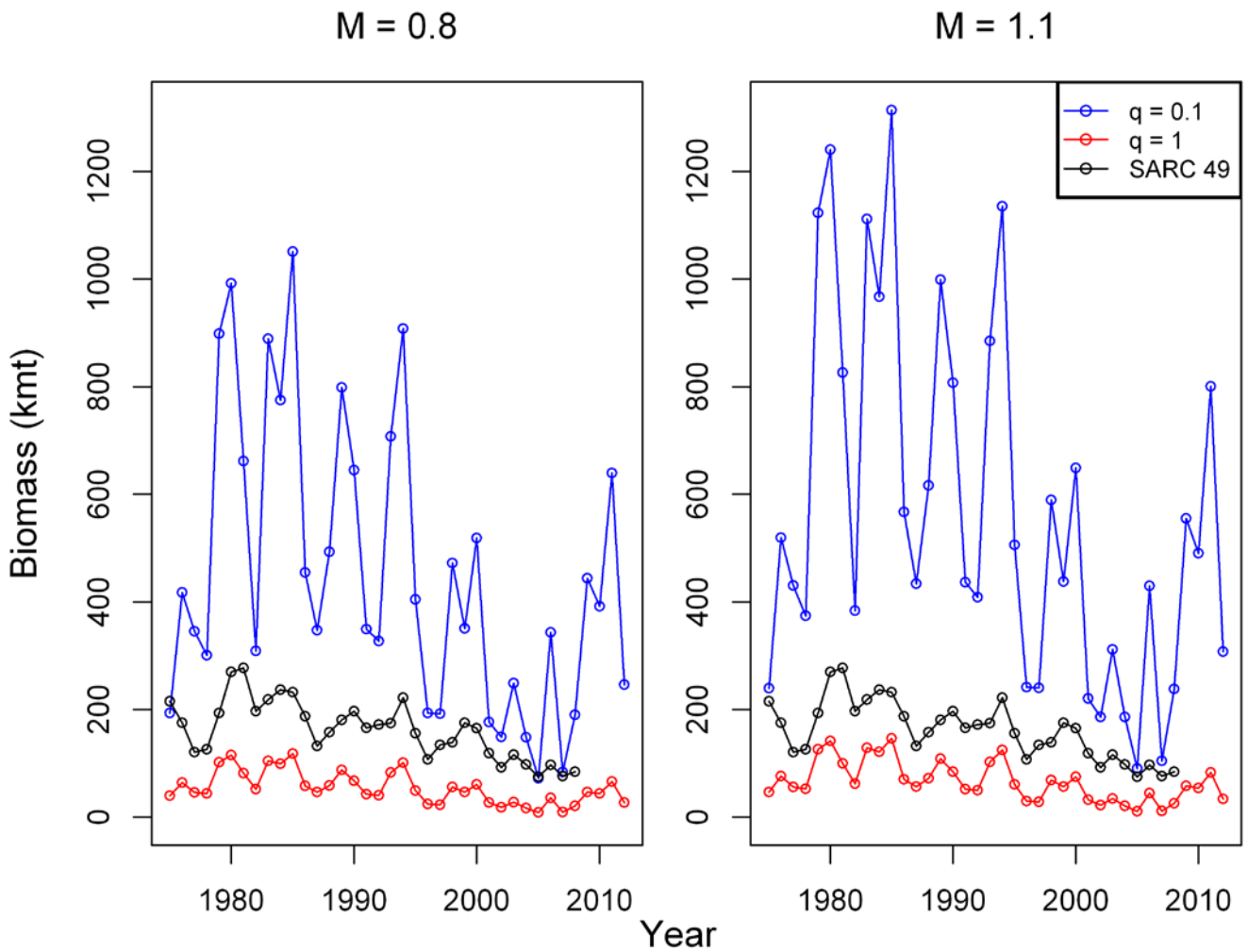

Figure 3. Implied annual January 1 butterfish stock biomass under 2 different survey efficiency and natural mortality assumptions and the biomass estimates from SARC 49 (NEFSC 2010). See Equation 4.

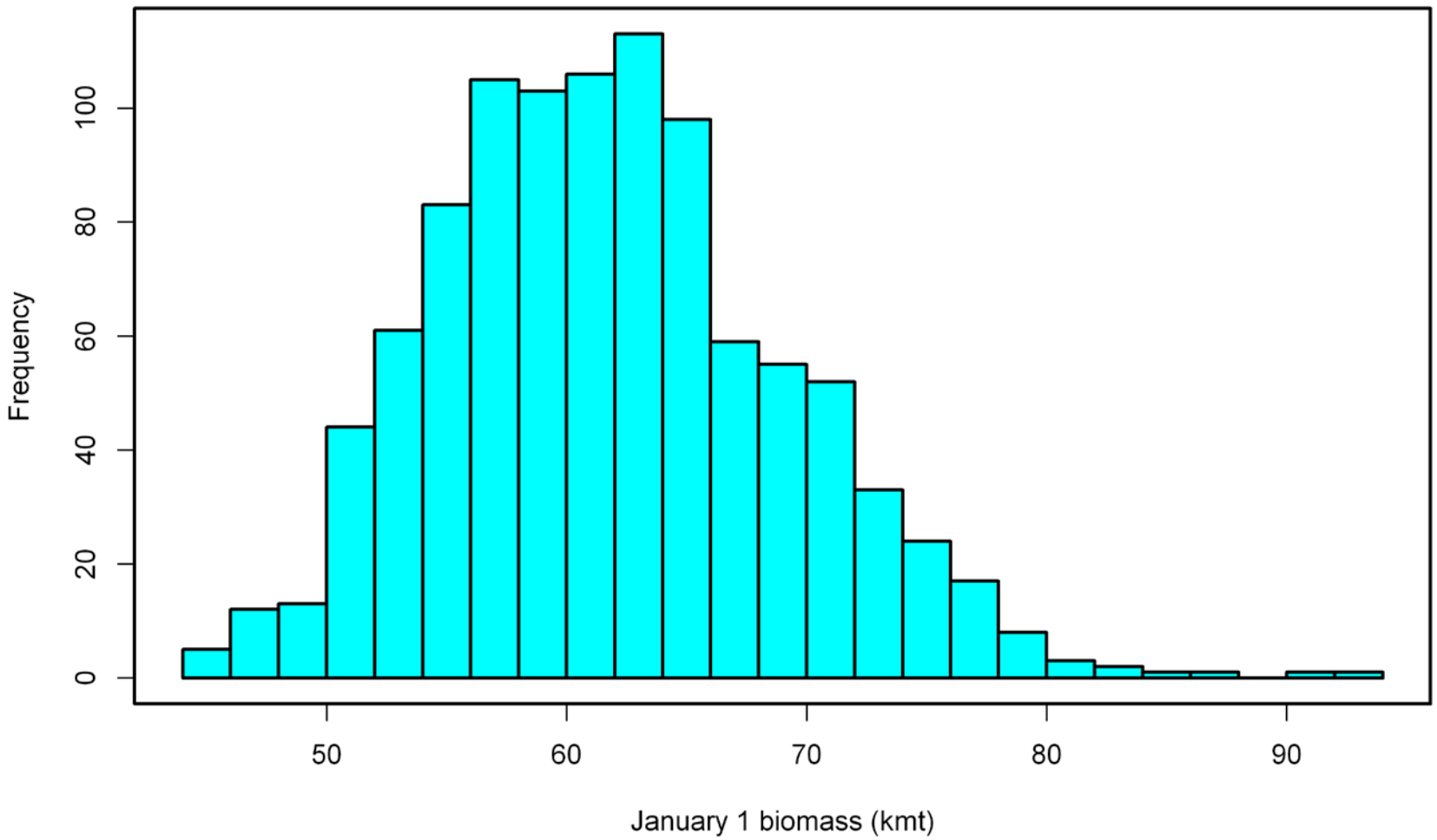

Figure 4. Histogram of 1000 parametric bootstraps of average January 1 biomasses for Atlantic butterfish in 2006-2012.

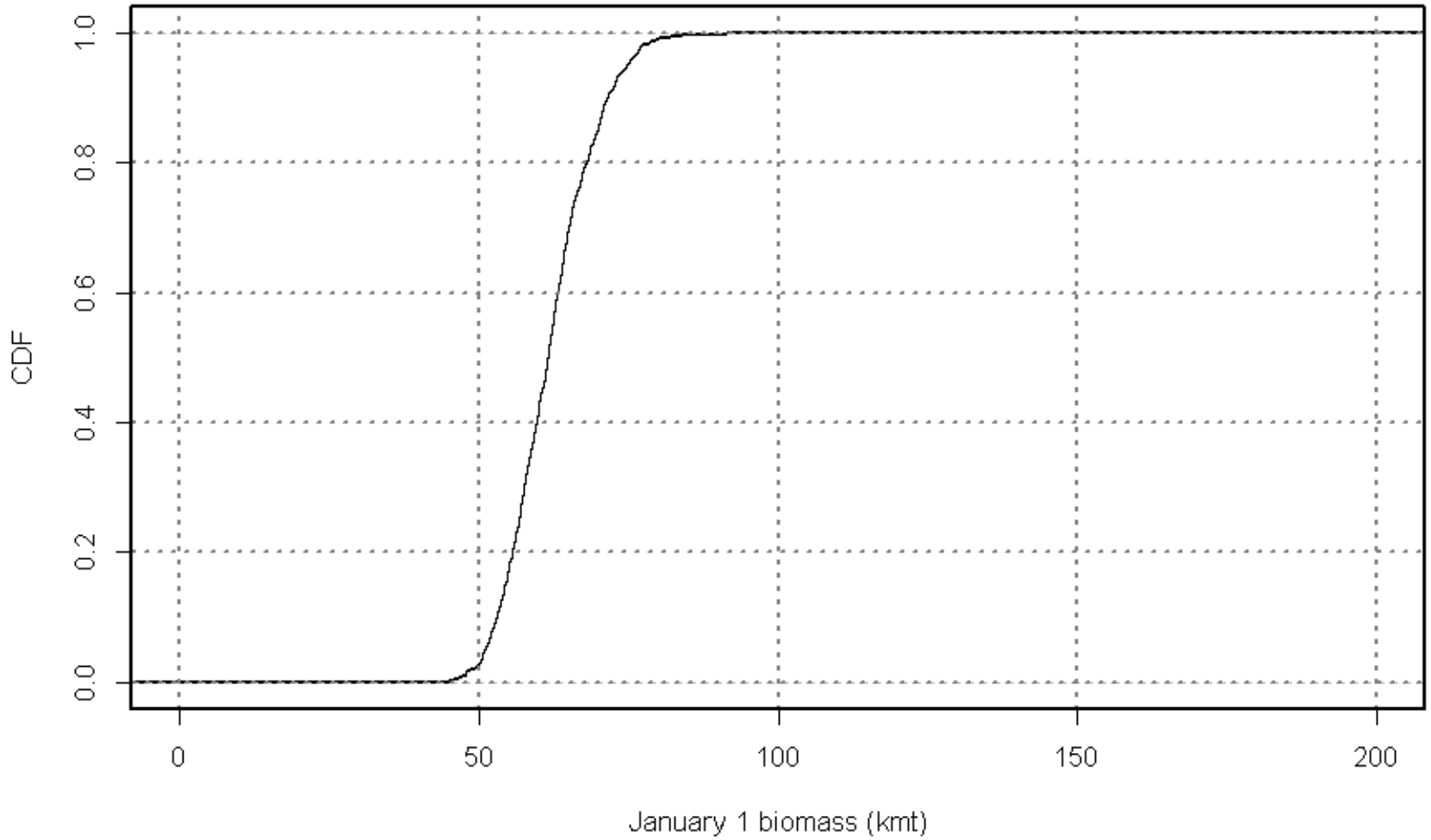

Figure 5. Cumulative distribution of 1000 parametric bootstraps of average January 1 biomasses for Atlantic butterfish in 2006-2012.

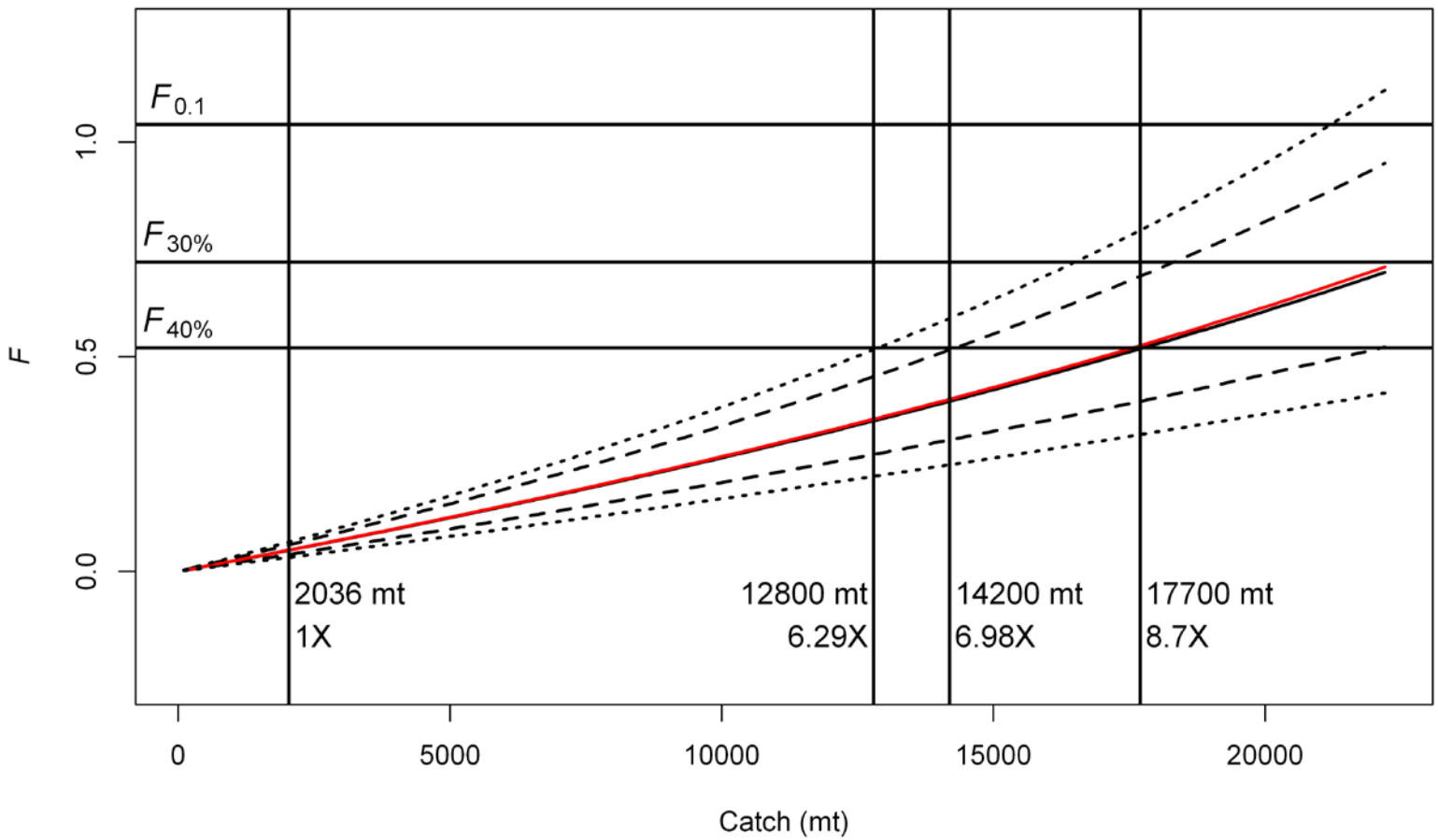

Figure 6. Mean (solid red), median (solid black), 0.025 and 0.975 confidence limits (dashed), minimum and maximum (dotted) of F for 1000 bootstraps, based on average 2006-2012 January 1 biomasses. Overfishing reference points are from SARC 49 (NEFSC 2010). Vertical lines are for average 2006-2012 total catch (1X); maximum (6.29X), 95% upper (6.98X), and median (8.7X) total catch associated with the most conservative stock size (q = 1 and M = 0.8) and fishing mortality equal to overfishing reference point ($F_{40\%} \approx 2M/3$).

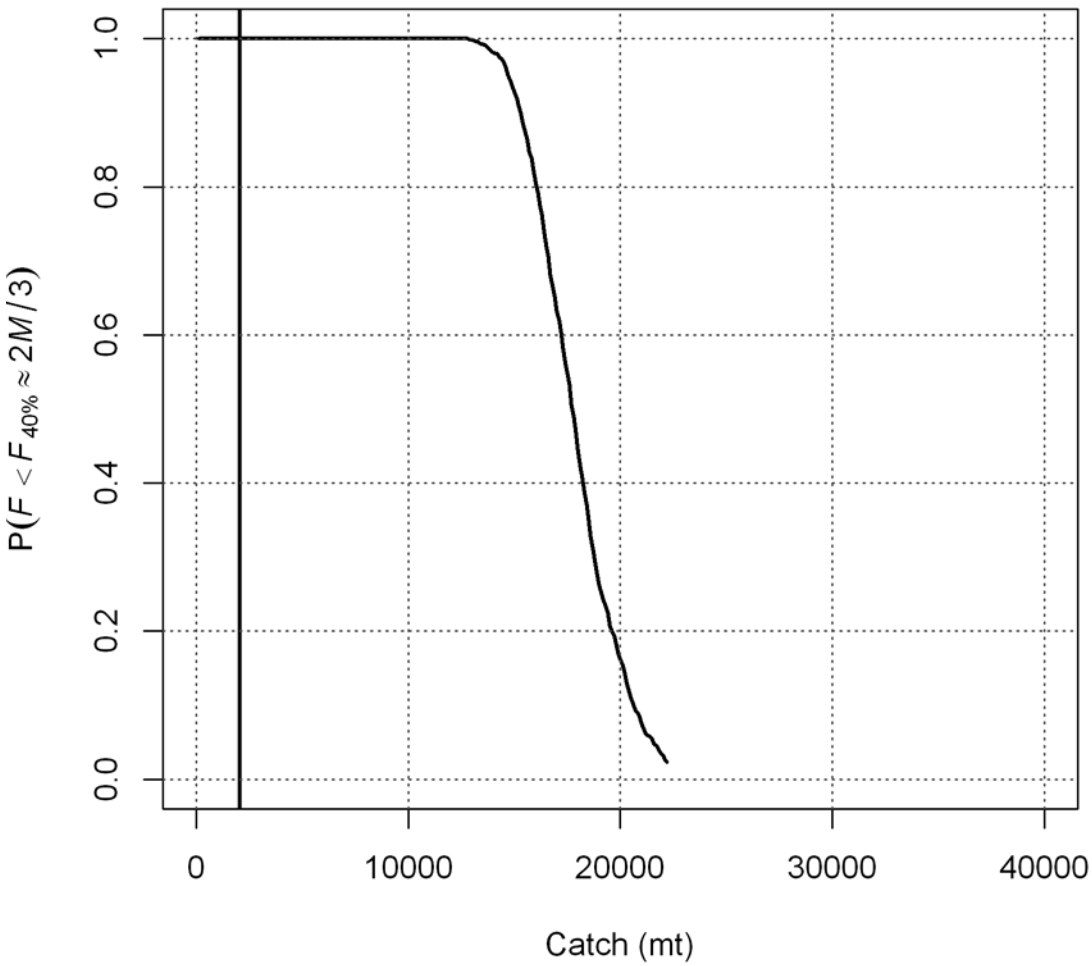

Figure 7. Probability fishing mortality at specified catch is less than $F_{40\%} \approx 2M/3$ based on parametric bootstrap of average 2006-2012 January 1 biomasses. Vertical line represents average annual catch 2006-2012.

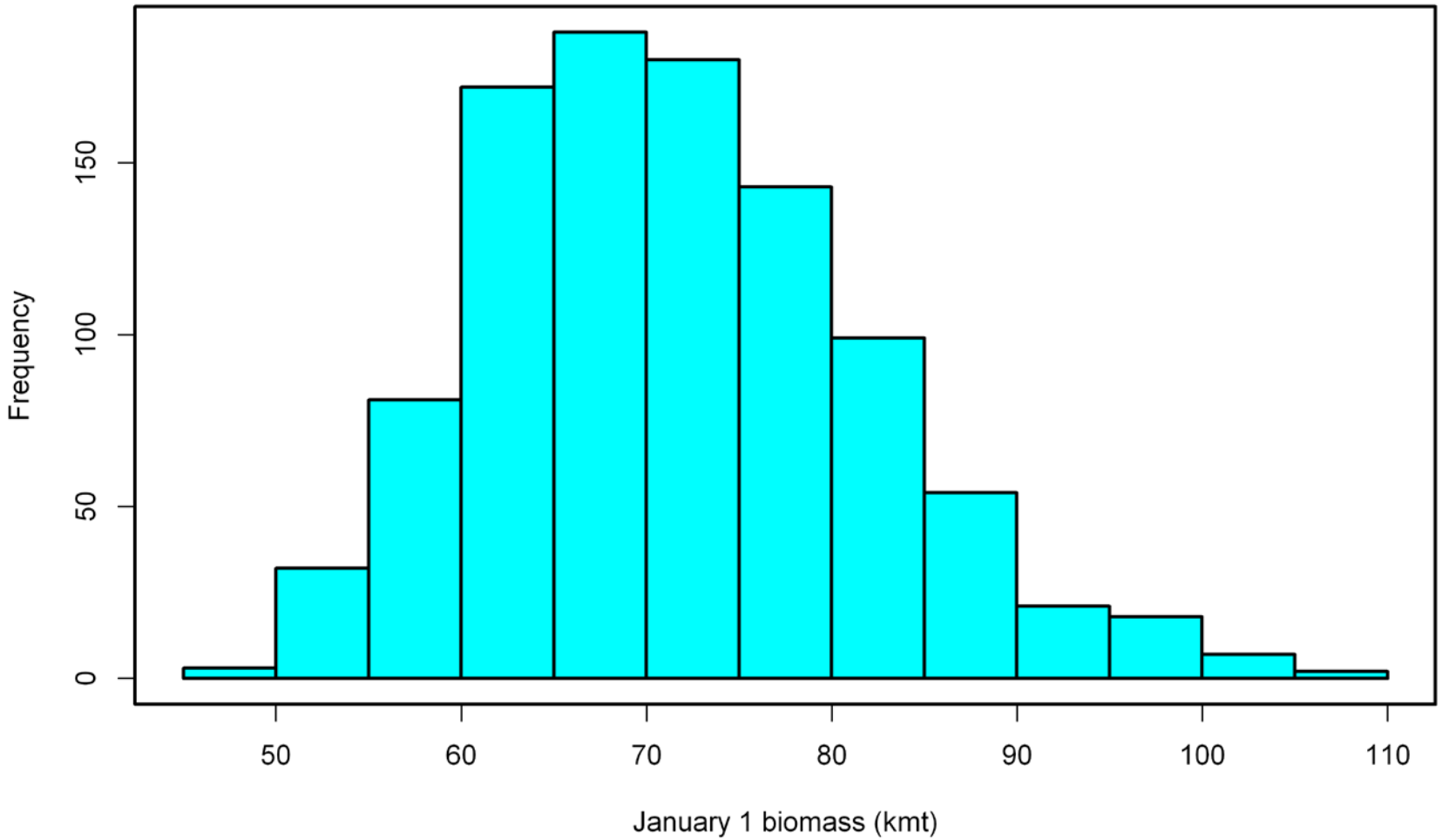

Figure 8. Histogram of 1000 parametric bootstraps of average January 1 biomasses for Atlantic butterfish in 2009-2012.

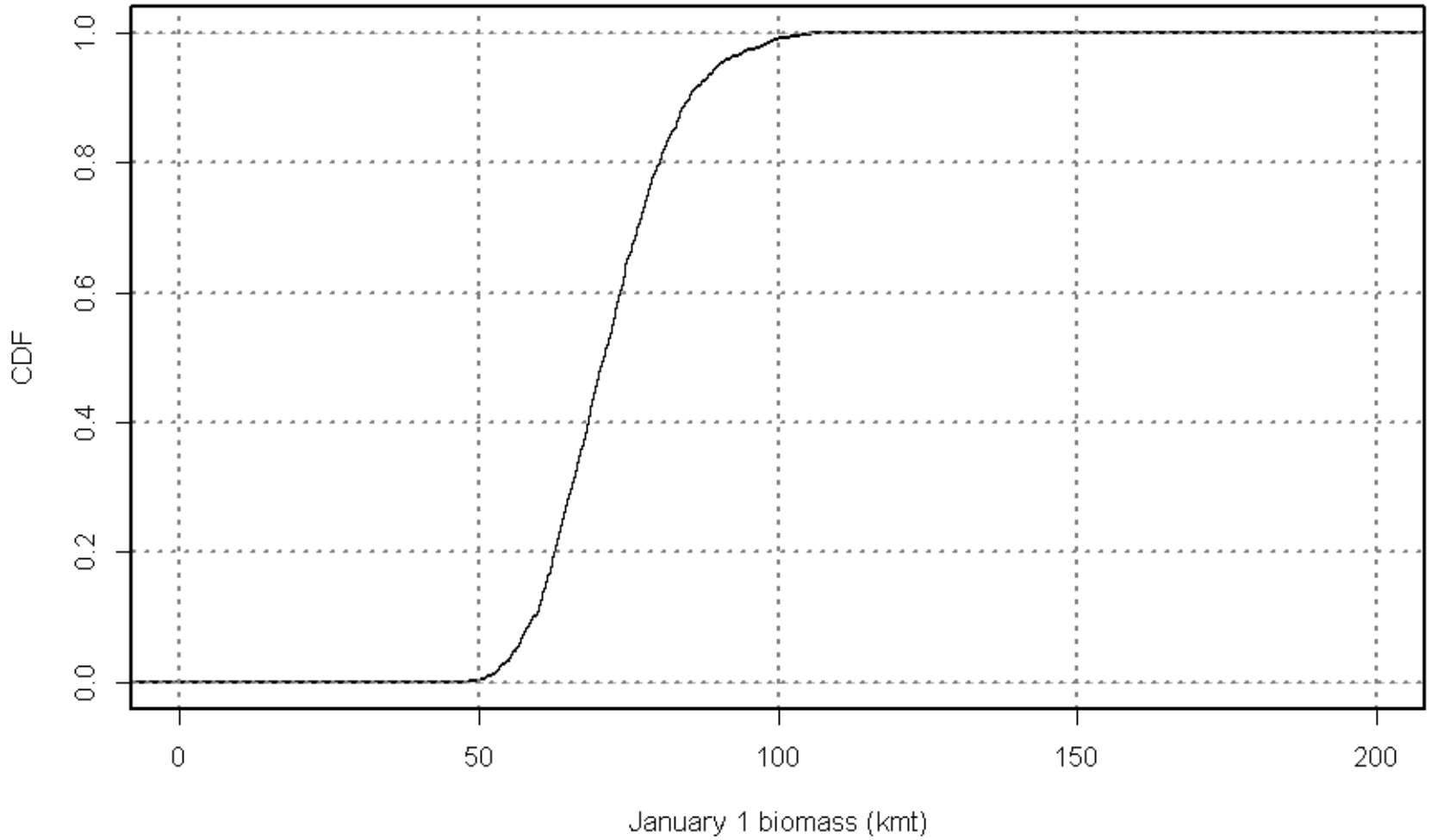

Figure 9. Cumulative distribution of 1000 parametric bootstraps of average January 1 biomasses for Atlantic butterfish in 2009-2012.

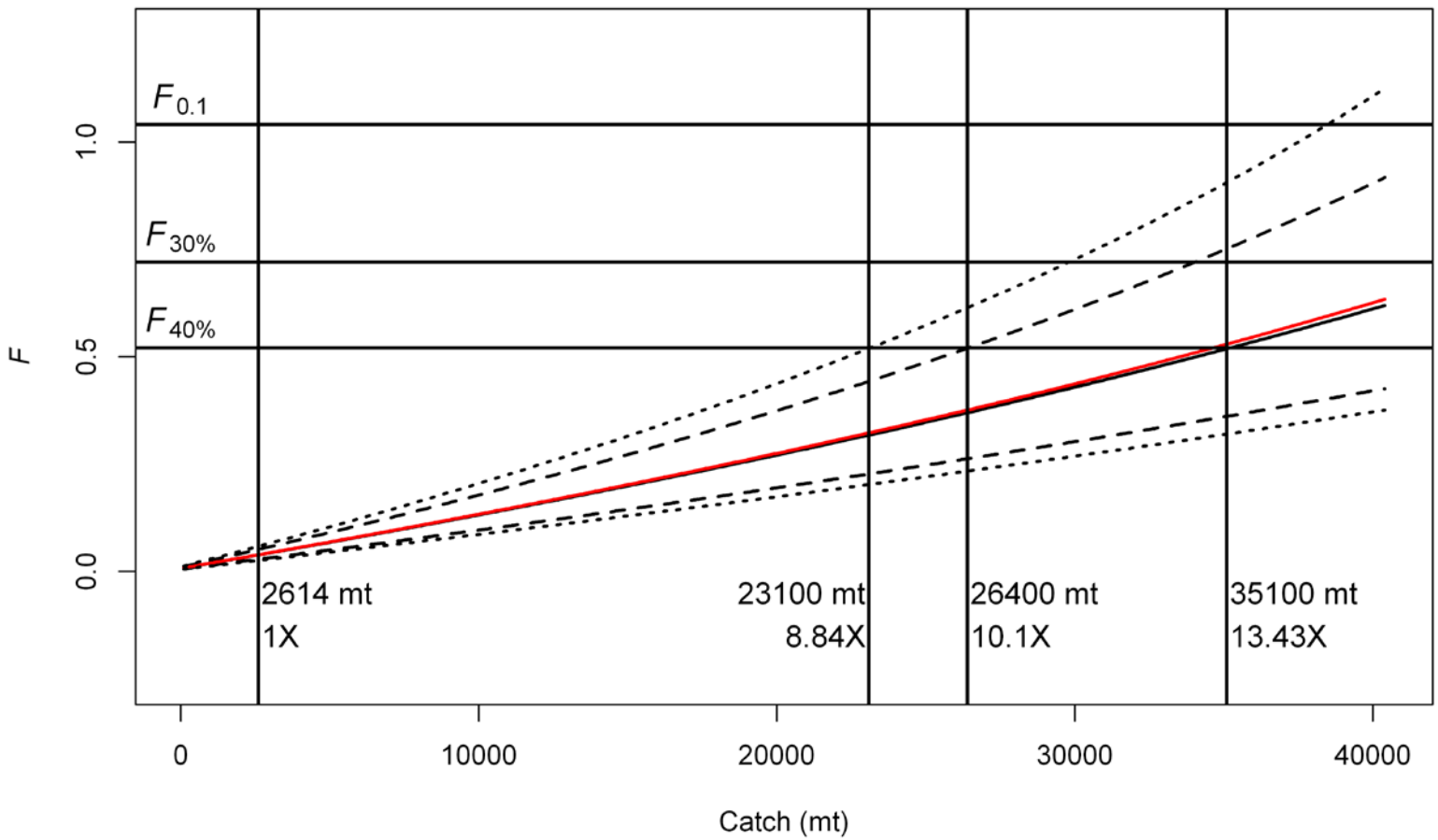

Figure 10. Mean (solid red), median (solid black), 0.025 and 0.975 confidence limits (dashed), minimum and maximum (dotted) of F for 1000 bootstraps, based on average 2009-2012 January 1 biomasses, and un-calibrated Bigelow data. Overfishing reference points are from SARC 49 (NEFSC 2010). Vertical lines are for average 2009-2012 total catch (1X); maximum (8.84X), 95% upper (10.1X), and median (13.43X) total catch associated with the most conservative stock size (q = 1 and M = 0.8) and fishing mortality equal to overfishing reference point ($F_{40\%} \approx 2M/3$).

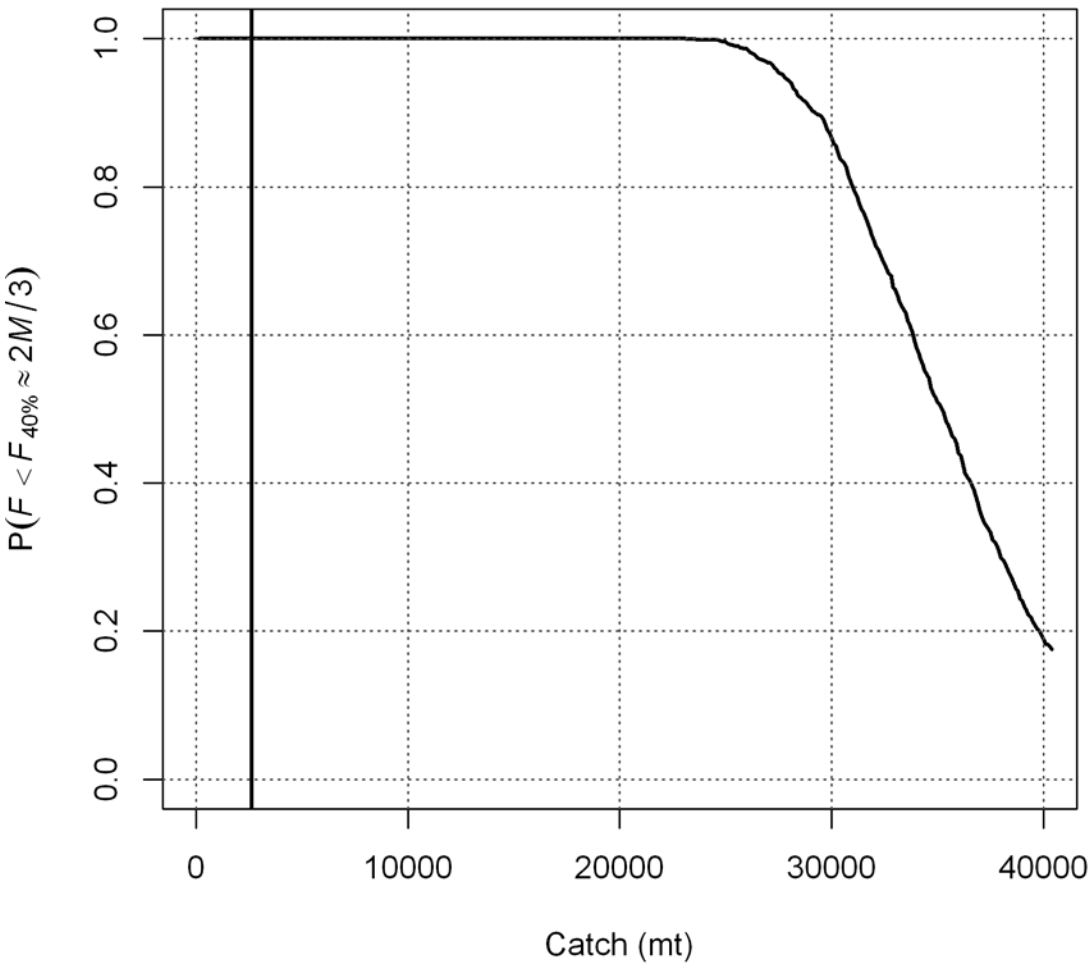

Figure 11. Probability fishing mortality at specified catch is less than $F_{40\%} \approx 2M/3$ based on parametric bootstrap of average 2009-2012 January 1 biomasses. Vertical line represents average annual catch 2009-2012.

Table 1. Annual NEFSC fall bottom trawl survey biomass index (kg/tow), survey area (*A*), average swept area per tow (*a*), landings (mt) discards (mt) and combined total catch (mt).

Year	Index	CV	*A*	*a*	Landings	Discards	Total Catch	CV
1975	2.51	0.31	41947	0.0112	14737	5148	19885	0.41
1976	5.79	0.23	41777	0.0112	15813	5663	21476	0.40
1977	4.84	0.31	42220	0.0112	4608	6599	11207	0.94
1978	4.16	0.16	42220	0.0112	5314	7971	13285	0.88
1979	12.69	0.22	42855	0.0112	3753	8443	12196	1.02
1980	14.00	0.54	42795	0.0112	6564	9126	15690	0.87
1981	9.29	0.30	42669	0.0112	6255	8744	14999	0.87
1982	4.11	0.29	42737	0.0112	10415	10214	20629	0.72
1983	12.52	0.23	42798	0.0112	5373	10037	15410	0.95
1984	10.81	0.30	42694	0.0112	12144	9494	21638	0.61
1985	14.85	0.24	42888	0.0112	5437	7703	13140	0.81
1986	6.33	0.19	42855	0.0112	4582	7397	11979	0.81
1987	4.80	0.29	42893	0.0112	4578	6905	11483	0.74
1988	6.93	0.19	42855	0.0112	2107	6921	9028	0.93
1989	11.40	0.29	42572	0.0112	3216	4480	7696	0.49
1990	9.23	0.23	42750	0.0112	2298	533	2831	0.07
1991	4.89	0.37	42945	0.0112	2189	4887	7076	0.68
1992	4.57	0.26	42788	0.0112	2754	5025	7779	0.35
1993	9.97	0.23	42795	0.0112	4608	7577	12185	0.20
1994	12.85	0.35	42888	0.0112	3634	6300	9934	0.23
1995	5.69	0.27	42687	0.0112	2067	6466	8533	0.38
1996	2.69	0.27	42945	0.0112	3555	1047	4602	0.16
1997	2.70	0.23	42855	0.0112	2794	986	3780	0.27
1998	6.62	0.39	42945	0.0112	1966	6378	8344	1.29
1999	4.84	0.30	42945	0.0112	2110	8927	11037	0.29
2000	7.30	0.25	42888	0.0112	1449	7015	8464	0.19
2001	2.40	0.40	42828	0.0112	4404	4474	8878	0.24
2002	2.08	0.22	42870	0.0112	872	2348	3220	0.91
2003	3.54	0.20	42660	0.0112	536	2114	2650	1.15
2004	2.10	0.36	42780	0.0112	497	1320	1783	0.21
2005	1.02	0.30	42705	0.0112	428	648	1077	0.13
2006	4.89	0.22	42893	0.0112	555	839	1393	0.44
2007	1.18	0.39	42945	0.0112	679	241	919	0.16
2008	2.70	0.22	42945	0.0112	452	1029	1481	0.44
2009	6.32	0.25	42945	0.0112	435	1298	1733	0.20
2010	5.59	0.30	42593	0.0112	576	3576	4152	0.31
2011	9.12	0.27	42945	0.0112	664	1555	2218	0.11
2012	3.48	0.42	42945	0.0112	627	1726*	2353	0.30*

* 2012 discards and associated CV are preliminary estimates using the quota monitoring (cumulative) methodology. As a comparison, the cumulative methodology estimate of 2011 discards was 1437 mt, with a CV of 0.13

Table 2. Annual NEFSC fall bottom trawl survey biomass index (kg/tow) using un-calibrated Bigelow data, survey area (*A*), average Bigelow swept area per tow (*a*), landings (mt) discards (mt) and combined total catch (mt).

Year	Index	CV	*A*	*a*	Landings	Discards	Total Catch	CV
2009	11.43	0.25	42945	0.007	435	1298	1733	0.20
2010	10.11	0.30	42593	0.007	576	3576	4152	0.31
2011	16.48	0.27	42945	0.007	664	1555	2218	0.11
2012	6.29	0.42	42945	0.007	627	1726*	2353	0.30*

* 2012 discards and associated CV are preliminary estimates using the quota monitoring (cumulative) methodology. As a comparison, the cumulative methodology estimate of 2011 discards was 1437 mt, with a CV of 0.13

Table 3. Range, 0.025 and 0.975 quantiles, and median fishing mortalities implied by specified catches from bootstrapped January 1 biomasses between years 2006 and 2012 when M = 0.8 and q = 1 is assumed.

Catch	Minimum	Maximum	0.025 Quantile	Median	0.975 Quantile
100	0.00	0.00	0.00	0.00	0.00
200	0.00	0.01	0.00	0.00	0.01
300	0.00	0.01	0.01	0.01	0.01
400	0.01	0.01	0.01	0.01	0.01
500	0.01	0.02	0.01	0.01	0.01
600	0.01	0.02	0.01	0.01	0.02
700	0.01	0.02	0.01	0.02	0.02
800	0.01	0.03	0.02	0.02	0.02
900	0.01	0.03	0.02	0.02	0.03
1000	0.02	0.03	0.02	0.02	0.03
1100	0.02	0.04	0.02	0.03	0.03
1200	0.02	0.04	0.02	0.03	0.04
1300	0.02	0.04	0.02	0.03	0.04
1400	0.02	0.05	0.03	0.03	0.04
1500	0.02	0.05	0.03	0.04	0.04
1600	0.03	0.05	0.03	0.04	0.05
1700	0.03	0.06	0.03	0.04	0.05
1800	0.03	0.06	0.03	0.04	0.05
1900	0.03	0.06	0.04	0.05	0.06
2000	0.03	0.07	0.04	0.05	0.06
2100	0.03	0.07	0.04	0.05	0.06
2200	0.04	0.07	0.04	0.05	0.07
2300	0.04	0.08	0.04	0.06	0.07
2400	0.04	0.08	0.05	0.06	0.07
2500	0.04	0.08	0.05	0.06	0.08
2600	0.04	0.09	0.05	0.06	0.08
2700	0.04	0.09	0.05	0.07	0.08
2800	0.04	0.10	0.05	0.07	0.09
2900	0.05	0.10	0.06	0.07	0.09
3000	0.05	0.10	0.06	0.07	0.09
3100	0.05	0.11	0.06	0.08	0.09
3200	0.05	0.11	0.06	0.08	0.10
3300	0.05	0.11	0.06	0.08	0.10
3400	0.05	0.12	0.07	0.08	0.10
3500	0.06	0.12	0.07	0.09	0.11
3600	0.06	0.12	0.07	0.09	0.11
3700	0.06	0.13	0.07	0.09	0.11

3800	0.06	0.13	0.07	0.09	0.12
3900	0.06	0.13	0.08	0.10	0.12
4000	0.06	0.14	0.08	0.10	0.12
4100	0.07	0.14	0.08	0.10	0.13
4200	0.07	0.15	0.08	0.10	0.13
4300	0.07	0.15	0.08	0.11	0.13
4400	0.07	0.15	0.09	0.11	0.14
4500	0.07	0.16	0.09	0.11	0.14
4600	0.07	0.16	0.09	0.11	0.14
4700	0.08	0.16	0.09	0.12	0.15
4800	0.08	0.17	0.09	0.12	0.15
4900	0.08	0.17	0.10	0.12	0.15
5000	0.08	0.18	0.10	0.12	0.16
5100	0.08	0.18	0.10	0.13	0.16
5200	0.08	0.18	0.10	0.13	0.16
5300	0.09	0.19	0.11	0.13	0.17
5400	0.09	0.19	0.11	0.14	0.17
5500	0.09	0.19	0.11	0.14	0.17
5600	0.09	0.20	0.11	0.14	0.18
5700	0.09	0.20	0.11	0.14	0.18
5800	0.10	0.21	0.12	0.15	0.18
5900	0.10	0.21	0.12	0.15	0.19
6000	0.10	0.21	0.12	0.15	0.19
6100	0.10	0.22	0.12	0.15	0.19
6200	0.10	0.22	0.12	0.16	0.20
6300	0.10	0.23	0.13	0.16	0.20
6400	0.11	0.23	0.13	0.16	0.20
6500	0.11	0.23	0.13	0.16	0.21
6600	0.11	0.24	0.13	0.17	0.21
6700	0.11	0.24	0.13	0.17	0.22
6800	0.11	0.25	0.14	0.17	0.22
6900	0.11	0.25	0.14	0.18	0.22
7000	0.12	0.25	0.14	0.18	0.23
7100	0.12	0.26	0.14	0.18	0.23
7200	0.12	0.26	0.15	0.18	0.23
7300	0.12	0.27	0.15	0.19	0.24
7400	0.12	0.27	0.15	0.19	0.24
7500	0.12	0.27	0.15	0.19	0.24
7600	0.13	0.28	0.15	0.20	0.25
7700	0.13	0.28	0.16	0.20	0.25
7800	0.13	0.29	0.16	0.20	0.26

7900	0.13	0.29	0.16	0.20	0.26
8000	0.13	0.30	0.16	0.21	0.26
8100	0.14	0.30	0.16	0.21	0.27
8200	0.14	0.30	0.17	0.21	0.27
8300	0.14	0.31	0.17	0.21	0.27
8400	0.14	0.31	0.17	0.22	0.28
8500	0.14	0.32	0.17	0.22	0.28
8600	0.14	0.32	0.18	0.22	0.28
8700	0.15	0.33	0.18	0.23	0.29
8800	0.15	0.33	0.18	0.23	0.29
8900	0.15	0.33	0.18	0.23	0.30
9000	0.15	0.34	0.18	0.23	0.30
9100	0.15	0.34	0.19	0.24	0.30
9200	0.15	0.35	0.19	0.24	0.31
9300	0.16	0.35	0.19	0.24	0.31
9400	0.16	0.36	0.19	0.25	0.32
9500	0.16	0.36	0.20	0.25	0.32
9600	0.16	0.36	0.20	0.25	0.32
9700	0.16	0.37	0.20	0.26	0.33
9800	0.17	0.37	0.20	0.26	0.33
9900	0.17	0.38	0.20	0.26	0.33
10000	0.17	0.38	0.21	0.26	0.34
10100	0.17	0.39	0.21	0.27	0.34
10200	0.17	0.39	0.21	0.27	0.35
10300	0.17	0.40	0.21	0.27	0.35
10400	0.18	0.40	0.22	0.28	0.35
10500	0.18	0.41	0.22	0.28	0.36
10600	0.18	0.41	0.22	0.28	0.36
10700	0.18	0.41	0.22	0.29	0.37
10800	0.18	0.42	0.23	0.29	0.37
10900	0.19	0.42	0.23	0.29	0.37
11000	0.19	0.43	0.23	0.29	0.38
11100	0.19	0.43	0.23	0.30	0.38
11200	0.19	0.44	0.23	0.30	0.39
11300	0.19	0.44	0.24	0.30	0.39
11400	0.19	0.45	0.24	0.31	0.39
11500	0.20	0.45	0.24	0.31	0.40
11600	0.20	0.46	0.24	0.31	0.40
11700	0.20	0.46	0.25	0.32	0.41
11800	0.20	0.47	0.25	0.32	0.41
11900	0.20	0.47	0.25	0.32	0.42

12000	0.21	0.48	0.25	0.33	0.42
12100	0.21	0.48	0.26	0.33	0.42
12200	0.21	0.49	0.26	0.33	0.43
12300	0.21	0.49	0.26	0.33	0.43
12400	0.21	0.50	0.26	0.34	0.44
12500	0.22	0.50	0.26	0.34	0.44
12600	0.22	0.51	0.27	0.34	0.45
12700	0.22	0.51	0.27	0.35	0.45
12800	0.22	0.52	0.27	0.35	0.45
12900	0.22	0.52	0.27	0.35	0.46
13000	0.23	0.53	0.28	0.36	0.46
13100	0.23	0.53	0.28	0.36	0.47
13200	0.23	0.54	0.28	0.36	0.47
13300	0.23	0.54	0.28	0.37	0.48
13400	0.23	0.55	0.29	0.37	0.48
13500	0.23	0.55	0.29	0.37	0.48
13600	0.24	0.56	0.29	0.38	0.49
13700	0.24	0.56	0.29	0.38	0.49
13800	0.24	0.57	0.30	0.38	0.50
13900	0.24	0.57	0.30	0.39	0.50
14000	0.24	0.58	0.30	0.39	0.51
14100	0.25	0.58	0.30	0.39	0.51
14200	0.25	0.59	0.31	0.40	0.52
14300	0.25	0.59	0.31	0.40	0.52
14400	0.25	0.60	0.31	0.40	0.52
14500	0.25	0.61	0.31	0.41	0.53
14600	0.26	0.61	0.32	0.41	0.53
14700	0.26	0.62	0.32	0.41	0.54
14800	0.26	0.62	0.32	0.42	0.54
14900	0.26	0.63	0.32	0.42	0.55
15000	0.26	0.63	0.33	0.42	0.55
15100	0.27	0.64	0.33	0.43	0.56
15200	0.27	0.64	0.33	0.43	0.56
15300	0.27	0.65	0.33	0.43	0.57
15400	0.27	0.66	0.34	0.44	0.57
15500	0.27	0.66	0.34	0.44	0.58
15600	0.28	0.67	0.34	0.44	0.58
15700	0.28	0.67	0.34	0.45	0.59
15800	0.28	0.68	0.35	0.45	0.59
15900	0.28	0.68	0.35	0.45	0.60
16000	0.28	0.69	0.35	0.46	0.60

16100	0.29	0.70	0.35	0.46	0.61
16200	0.29	0.70	0.36	0.46	0.61
16300	0.29	0.71	0.36	0.47	0.62
16400	0.29	0.71	0.36	0.47	0.62
16500	0.29	0.72	0.36	0.47	0.63
16600	0.30	0.73	0.37	0.48	0.63
16700	0.30	0.73	0.37	0.48	0.64
16800	0.30	0.74	0.37	0.49	0.64
16900	0.30	0.74	0.37	0.49	0.65
17000	0.30	0.75	0.38	0.49	0.65
17100	0.31	0.76	0.38	0.50	0.66
17200	0.31	0.76	0.38	0.50	0.66
17300	0.31	0.77	0.39	0.50	0.67
17400	0.31	0.78	0.39	0.51	0.67
17500	0.31	0.78	0.39	0.51	0.68
17600	0.32	0.79	0.39	0.51	0.68
17700	0.32	0.79	0.40	0.52	0.69
17800	0.32	0.80	0.40	0.52	0.69
17900	0.32	0.81	0.40	0.53	0.70
18000	0.32	0.81	0.40	0.53	0.70
18100	0.33	0.82	0.41	0.53	0.71
18200	0.33	0.83	0.41	0.54	0.71
18300	0.33	0.83	0.41	0.54	0.72
18400	0.33	0.84	0.41	0.54	0.72
18500	0.34	0.85	0.42	0.55	0.73
18600	0.34	0.85	0.42	0.55	0.74
18700	0.34	0.86	0.42	0.56	0.74
18800	0.34	0.87	0.43	0.56	0.75
18900	0.34	0.87	0.43	0.56	0.75
19000	0.35	0.88	0.43	0.57	0.76
19100	0.35	0.89	0.43	0.57	0.76
19200	0.35	0.89	0.44	0.57	0.77
19300	0.35	0.90	0.44	0.58	0.77
19400	0.35	0.91	0.44	0.58	0.78
19500	0.36	0.91	0.44	0.59	0.79
19600	0.36	0.92	0.45	0.59	0.79
19700	0.36	0.93	0.45	0.59	0.80
19800	0.36	0.94	0.45	0.60	0.80
19900	0.36	0.94	0.46	0.60	0.81
20000	0.37	0.95	0.46	0.61	0.81
20100	0.37	0.96	0.46	0.61	0.82

20200	0.37	0.96	0.46	0.61	0.83
20300	0.37	0.97	0.47	0.62	0.83
20400	0.38	0.98	0.47	0.62	0.84
20500	0.38	0.99	0.47	0.63	0.84
20600	0.38	0.99	0.48	0.63	0.85
20700	0.38	1.00	0.48	0.63	0.86
20800	0.38	1.01	0.48	0.64	0.86
20900	0.39	1.02	0.48	0.64	0.87
21000	0.39	1.02	0.49	0.65	0.87
21100	0.39	1.03	0.49	0.65	0.88
21200	0.39	1.04	0.49	0.65	0.89
21300	0.40	1.05	0.50	0.66	0.89
21400	0.40	1.06	0.50	0.66	0.90
21500	0.40	1.06	0.50	0.67	0.91
21600	0.40	1.07	0.50	0.67	0.91
21700	0.40	1.08	0.51	0.68	0.92
21800	0.41	1.09	0.51	0.68	0.92
21900	0.41	1.10	0.51	0.68	0.93
22000	0.41	1.10	0.52	0.69	0.94
22100	0.41	1.11	0.52	0.69	0.94
22200	0.42	1.12	0.52	0.70	0.95

Table 4. Range, 0..25 and 0.975 quantiles, and median fishing mortalities implied by specified catches from bootstrapped January 1 biomasses between years 2009 and 2012 when M = 0.8 and q = 1 is assumed.

Catch	Minimum	Maximum	0.025 Quantile	Median	0.975 Quantile
100	0.01	0.01	0.01	0.01	0.01
200	0.01	0.01	0.01	0.01	0.01
300	0.01	0.02	0.01	0.01	0.01
400	0.01	0.02	0.01	0.01	0.02
500	0.01	0.02	0.01	0.01	0.02
600	0.01	0.02	0.01	0.01	0.02
700	0.01	0.02	0.01	0.02	0.02
800	0.01	0.03	0.01	0.02	0.02
900	0.01	0.03	0.01	0.02	0.02
1000	0.01	0.03	0.01	0.02	0.03
1100	0.01	0.03	0.01	0.02	0.03
1200	0.01	0.03	0.02	0.02	0.03
1300	0.01	0.03	0.02	0.02	0.03
1400	0.02	0.04	0.02	0.02	0.03
1500	0.02	0.04	0.02	0.02	0.03
1600	0.02	0.04	0.02	0.03	0.03
1700	0.02	0.04	0.02	0.03	0.04
1800	0.02	0.04	0.02	0.03	0.04
1900	0.02	0.05	0.02	0.03	0.04
2000	0.02	0.05	0.02	0.03	0.04
2100	0.02	0.05	0.02	0.03	0.04
2200	0.02	0.05	0.02	0.03	0.04
2300	0.02	0.05	0.03	0.03	0.05
2400	0.02	0.05	0.03	0.04	0.05
2500	0.02	0.06	0.03	0.04	0.05
2600	0.03	0.06	0.03	0.04	0.05
2700	0.03	0.06	0.03	0.04	0.05
2800	0.03	0.06	0.03	0.04	0.05
2900	0.03	0.06	0.03	0.04	0.06
3000	0.03	0.07	0.03	0.04	0.06
3100	0.03	0.07	0.03	0.04	0.06
3200	0.03	0.07	0.03	0.05	0.06
3300	0.03	0.07	0.03	0.05	0.06
3400	0.03	0.07	0.04	0.05	0.06
3500	0.03	0.07	0.04	0.05	0.07
3600	0.03	0.08	0.04	0.05	0.07
3700	0.03	0.08	0.04	0.05	0.07

3800	0.03	0.08	0.04	0.05	0.07
3900	0.04	0.08	0.04	0.05	0.07
4000	0.04	0.08	0.04	0.06	0.07
4100	0.04	0.09	0.04	0.06	0.08
4200	0.04	0.09	0.04	0.06	0.08
4300	0.04	0.09	0.04	0.06	0.08
4400	0.04	0.09	0.04	0.06	0.08
4500	0.04	0.09	0.05	0.06	0.08
4600	0.04	0.10	0.05	0.06	0.08
4700	0.04	0.10	0.05	0.06	0.09
4800	0.04	0.10	0.05	0.07	0.09
4900	0.04	0.10	0.05	0.07	0.09
5000	0.04	0.10	0.05	0.07	0.09
5100	0.05	0.11	0.05	0.07	0.09
5200	0.05	0.11	0.05	0.07	0.09
5300	0.05	0.11	0.05	0.07	0.10
5400	0.05	0.11	0.05	0.07	0.10
5500	0.05	0.11	0.05	0.07	0.10
5600	0.05	0.12	0.06	0.08	0.10
5700	0.05	0.12	0.06	0.08	0.10
5800	0.05	0.12	0.06	0.08	0.10
5900	0.05	0.12	0.06	0.08	0.11
6000	0.05	0.12	0.06	0.08	0.11
6100	0.05	0.12	0.06	0.08	0.11
6200	0.05	0.13	0.06	0.08	0.11
6300	0.06	0.13	0.06	0.08	0.11
6400	0.06	0.13	0.06	0.09	0.11
6500	0.06	0.13	0.06	0.09	0.12
6600	0.06	0.13	0.06	0.09	0.12
6700	0.06	0.14	0.07	0.09	0.12
6800	0.06	0.14	0.07	0.09	0.12
6900	0.06	0.14	0.07	0.09	0.12
7000	0.06	0.14	0.07	0.09	0.12
7100	0.06	0.14	0.07	0.09	0.13
7200	0.06	0.15	0.07	0.10	0.13
7300	0.06	0.15	0.07	0.10	0.13
7400	0.06	0.15	0.07	0.10	0.13
7500	0.07	0.15	0.07	0.10	0.13
7600	0.07	0.15	0.07	0.10	0.13
7700	0.07	0.16	0.07	0.10	0.14
7800	0.07	0.16	0.08	0.10	0.14

7900	0.07	0.16	0.08	0.10	0.14
8000	0.07	0.16	0.08	0.11	0.14
8100	0.07	0.17	0.08	0.11	0.14
8200	0.07	0.17	0.08	0.11	0.15
8300	0.07	0.17	0.08	0.11	0.15
8400	0.07	0.17	0.08	0.11	0.15
8500	0.07	0.17	0.08	0.11	0.15
8600	0.07	0.18	0.08	0.11	0.15
8700	0.08	0.18	0.08	0.11	0.15
8800	0.08	0.18	0.08	0.12	0.16
8900	0.08	0.18	0.09	0.12	0.16
9000	0.08	0.18	0.09	0.12	0.16
9100	0.08	0.19	0.09	0.12	0.16
9200	0.08	0.19	0.09	0.12	0.16
9300	0.08	0.19	0.09	0.12	0.16
9400	0.08	0.19	0.09	0.12	0.17
9500	0.08	0.19	0.09	0.12	0.17
9600	0.08	0.20	0.09	0.13	0.17
9700	0.08	0.20	0.09	0.13	0.17
9800	0.08	0.20	0.09	0.13	0.17
9900	0.09	0.20	0.10	0.13	0.18
10000	0.09	0.20	0.10	0.13	0.18
10100	0.09	0.21	0.10	0.13	0.18
10200	0.09	0.21	0.10	0.13	0.18
10300	0.09	0.21	0.10	0.14	0.18
10400	0.09	0.21	0.10	0.14	0.18
10500	0.09	0.22	0.10	0.14	0.19
10600	0.09	0.22	0.10	0.14	0.19
10700	0.09	0.22	0.10	0.14	0.19
10800	0.09	0.22	0.10	0.14	0.19
10900	0.09	0.22	0.10	0.14	0.19
11000	0.09	0.23	0.11	0.14	0.20
11100	0.10	0.23	0.11	0.15	0.20
11200	0.10	0.23	0.11	0.15	0.20
11300	0.10	0.23	0.11	0.15	0.20
11400	0.10	0.23	0.11	0.15	0.20
11500	0.10	0.24	0.11	0.15	0.20
11600	0.10	0.24	0.11	0.15	0.21
11700	0.10	0.24	0.11	0.15	0.21
11800	0.10	0.24	0.11	0.16	0.21
11900	0.10	0.25	0.11	0.16	0.21

12000	0.10	0.25	0.12	0.16	0.21
12100	0.10	0.25	0.12	0.16	0.22
12200	0.10	0.25	0.12	0.16	0.22
12300	0.11	0.25	0.12	0.16	0.22
12400	0.11	0.26	0.12	0.16	0.22
12500	0.11	0.26	0.12	0.16	0.22
12600	0.11	0.26	0.12	0.17	0.23
12700	0.11	0.26	0.12	0.17	0.23
12800	0.11	0.27	0.12	0.17	0.23
12900	0.11	0.27	0.12	0.17	0.23
13000	0.11	0.27	0.12	0.17	0.23
13100	0.11	0.27	0.13	0.17	0.24
13200	0.11	0.27	0.13	0.17	0.24
13300	0.11	0.28	0.13	0.18	0.24
13400	0.12	0.28	0.13	0.18	0.24
13500	0.12	0.28	0.13	0.18	0.24
13600	0.12	0.28	0.13	0.18	0.24
13700	0.12	0.29	0.13	0.18	0.25
13800	0.12	0.29	0.13	0.18	0.25
13900	0.12	0.29	0.13	0.18	0.25
14000	0.12	0.29	0.13	0.19	0.25
14100	0.12	0.29	0.14	0.19	0.25
14200	0.12	0.30	0.14	0.19	0.26
14300	0.12	0.30	0.14	0.19	0.26
14400	0.12	0.30	0.14	0.19	0.26
14500	0.12	0.30	0.14	0.19	0.26
14600	0.13	0.31	0.14	0.19	0.26
14700	0.13	0.31	0.14	0.19	0.27
14800	0.13	0.31	0.14	0.20	0.27
14900	0.13	0.31	0.14	0.20	0.27
15000	0.13	0.31	0.14	0.20	0.27
15100	0.13	0.32	0.15	0.20	0.27
15200	0.13	0.32	0.15	0.20	0.28
15300	0.13	0.32	0.15	0.20	0.28
15400	0.13	0.32	0.15	0.20	0.28
15500	0.13	0.33	0.15	0.21	0.28
15600	0.13	0.33	0.15	0.21	0.28
15700	0.14	0.33	0.15	0.21	0.29
15800	0.14	0.33	0.15	0.21	0.29
15900	0.14	0.34	0.15	0.21	0.29
16000	0.14	0.34	0.15	0.21	0.29

16100	0.14	0.34	0.16	0.21	0.29
16200	0.14	0.34	0.16	0.22	0.30
16300	0.14	0.35	0.16	0.22	0.30
16400	0.14	0.35	0.16	0.22	0.30
16500	0.14	0.35	0.16	0.22	0.30
16600	0.14	0.35	0.16	0.22	0.30
16700	0.14	0.36	0.16	0.22	0.31
16800	0.14	0.36	0.16	0.22	0.31
16900	0.15	0.36	0.16	0.23	0.31
17000	0.15	0.36	0.16	0.23	0.31
17100	0.15	0.36	0.17	0.23	0.31
17200	0.15	0.37	0.17	0.23	0.32
17300	0.15	0.37	0.17	0.23	0.32
17400	0.15	0.37	0.17	0.23	0.32
17500	0.15	0.37	0.17	0.23	0.32
17600	0.15	0.38	0.17	0.24	0.32
17700	0.15	0.38	0.17	0.24	0.33
17800	0.15	0.38	0.17	0.24	0.33
17900	0.15	0.38	0.17	0.24	0.33
18000	0.16	0.39	0.17	0.24	0.33
18100	0.16	0.39	0.18	0.24	0.33
18200	0.16	0.39	0.18	0.24	0.34
18300	0.16	0.39	0.18	0.25	0.34
18400	0.16	0.40	0.18	0.25	0.34
18500	0.16	0.40	0.18	0.25	0.34
18600	0.16	0.40	0.18	0.25	0.34
18700	0.16	0.40	0.18	0.25	0.35
18800	0.16	0.41	0.18	0.25	0.35
18900	0.16	0.41	0.18	0.25	0.35
19000	0.16	0.41	0.18	0.26	0.35
19100	0.17	0.41	0.19	0.26	0.35
19200	0.17	0.42	0.19	0.26	0.36
19300	0.17	0.42	0.19	0.26	0.36
19400	0.17	0.42	0.19	0.26	0.36
19500	0.17	0.42	0.19	0.26	0.36
19600	0.17	0.43	0.19	0.26	0.37
19700	0.17	0.43	0.19	0.27	0.37
19800	0.17	0.43	0.19	0.27	0.37
19900	0.17	0.43	0.19	0.27	0.37
20000	0.17	0.44	0.19	0.27	0.37
20100	0.17	0.44	0.20	0.27	0.38

20200	0.18	0.44	0.20	0.27	0.38
20300	0.18	0.44	0.20	0.28	0.38
20400	0.18	0.45	0.20	0.28	0.38
20500	0.18	0.45	0.20	0.28	0.38
20600	0.18	0.45	0.20	0.28	0.39
20700	0.18	0.46	0.20	0.28	0.39
20800	0.18	0.46	0.20	0.28	0.39
20900	0.18	0.46	0.20	0.28	0.39
21000	0.18	0.46	0.20	0.29	0.40
21100	0.18	0.47	0.21	0.29	0.40
21200	0.18	0.47	0.21	0.29	0.40
21300	0.19	0.47	0.21	0.29	0.40
21400	0.19	0.47	0.21	0.29	0.40
21500	0.19	0.48	0.21	0.29	0.41
21600	0.19	0.48	0.21	0.29	0.41
21700	0.19	0.48	0.21	0.30	0.41
21800	0.19	0.48	0.21	0.30	0.41
21900	0.19	0.49	0.21	0.30	0.42
22000	0.19	0.49	0.22	0.30	0.42

Appendix A. Length composition of landings and discards from observer data.

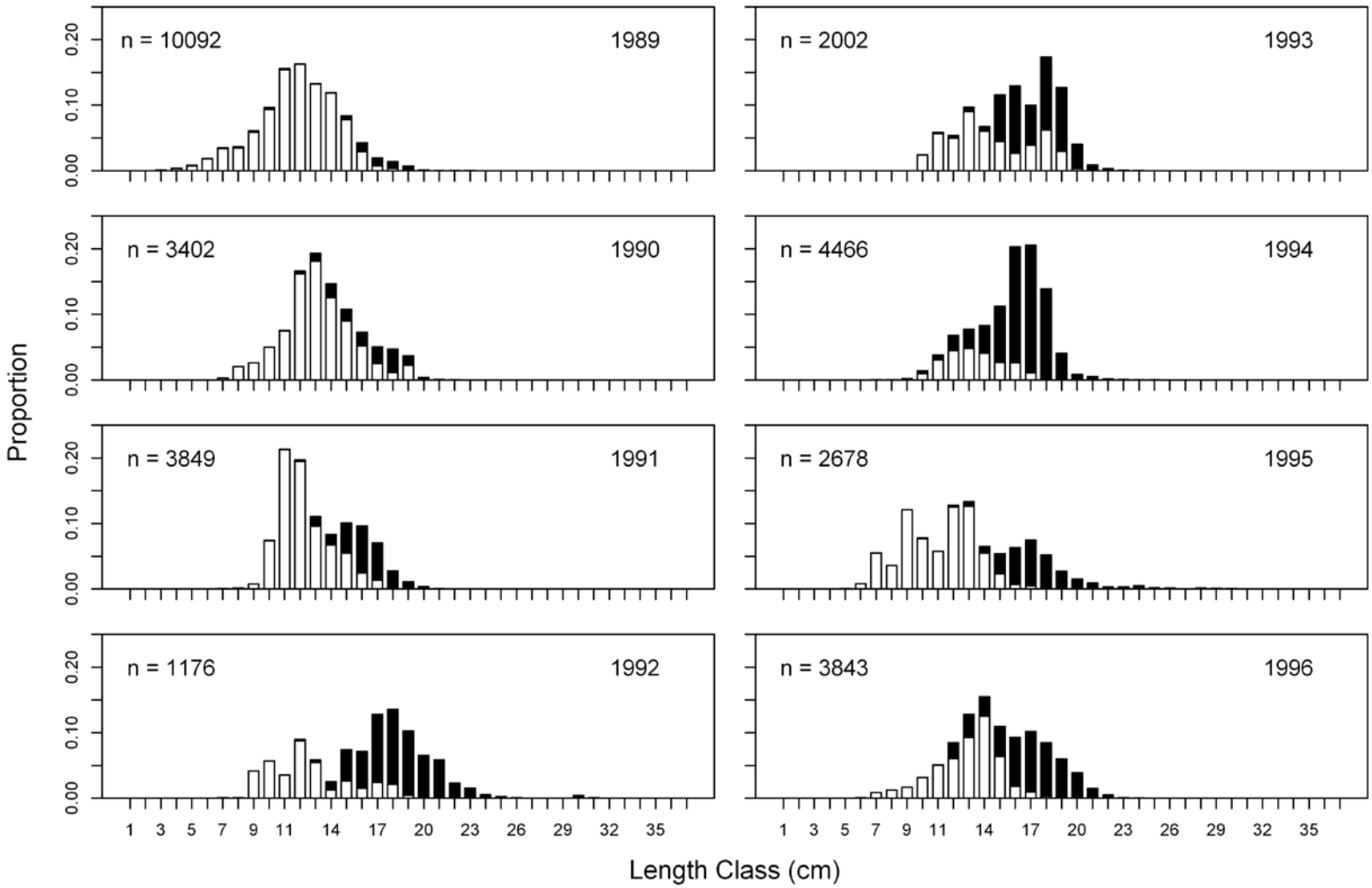

Figure A1. Length composition for NMFS Observer Program for butterfish between 1989 and 1996 with kept fish in black and discard in white. Size of a bar of a given color is the proportion of total length samples in the length interval and corresponding disposition.

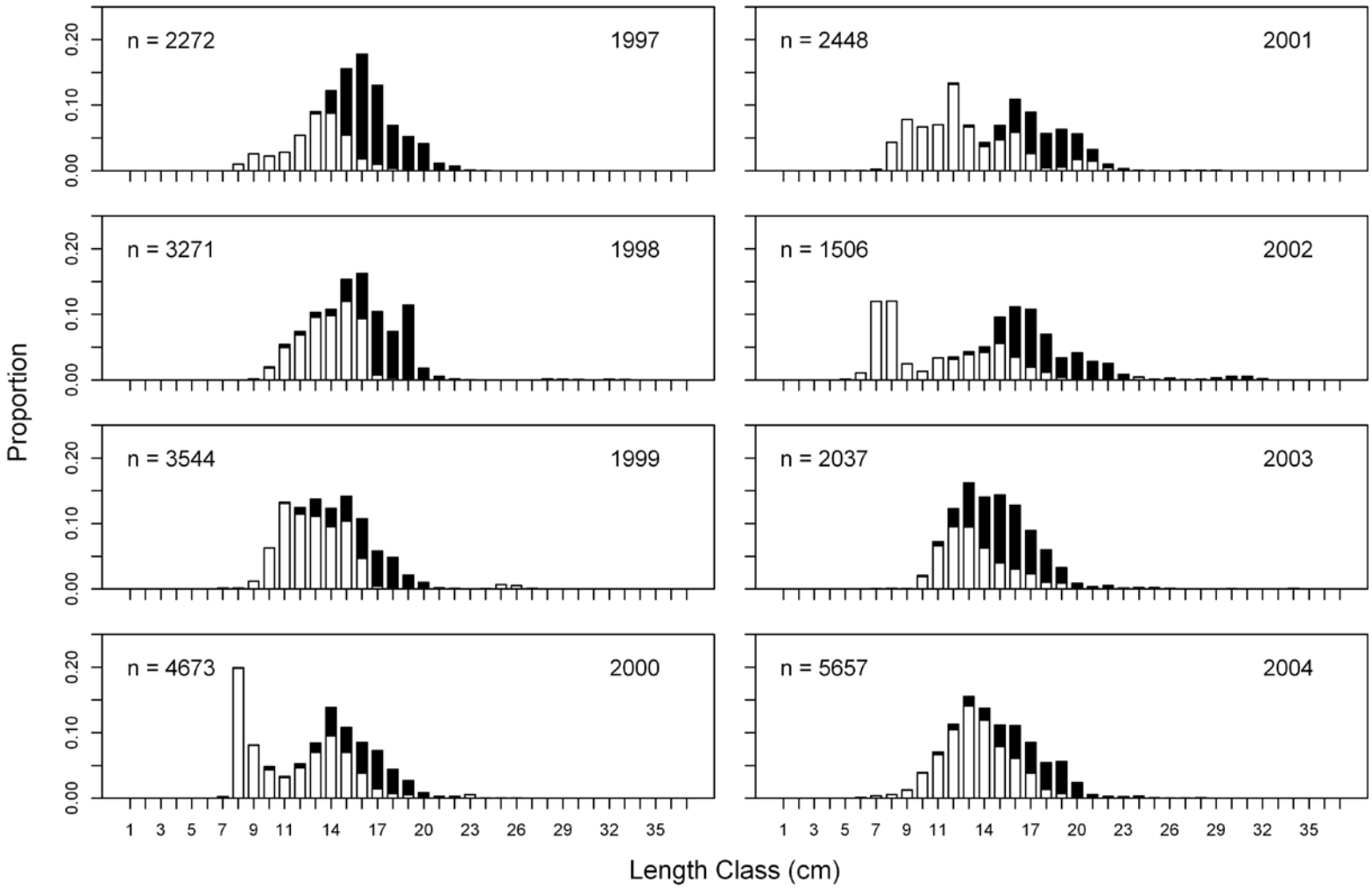

Figure A2. Length composition for NMFS Observer Program for butterfish between 1997 and 2004 with kept fish in black and discard in white. Size of a bar of a given color is the proportion of total length samples in the length interval and corresponding disposition.

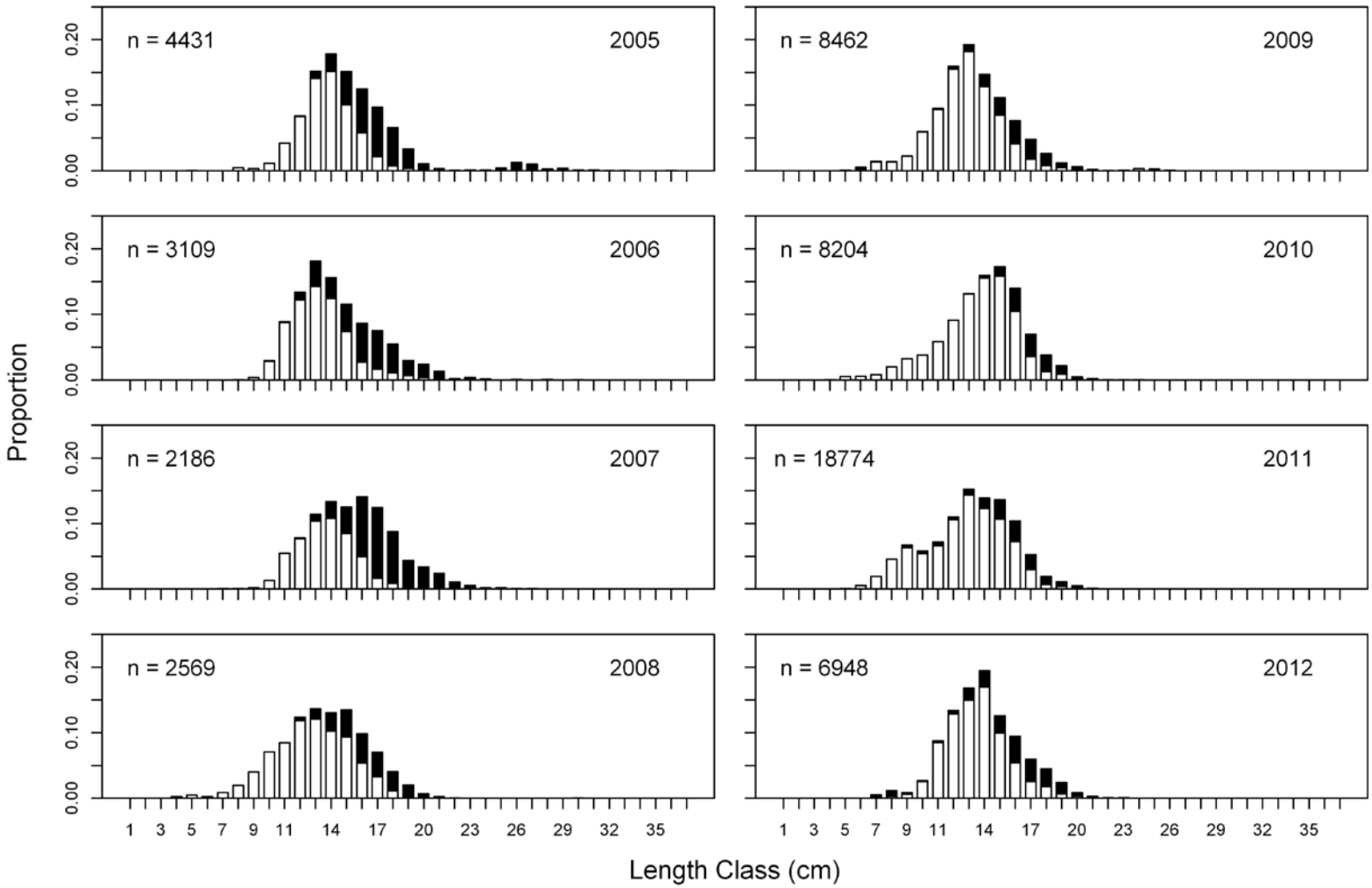

Figure A3. Length composition for NMFS Observer Program for butterfish between 2005 and 2012 with kept fish in black and discard in white. Size of a bar of a given color is the proportion of total length samples in the length interval and corresponding disposition.

Appendix 2. Abundance indices for NEFSC fall surveys.

Table B1. Abundance indices (number per tow) for NEFSC fall surveys in inshore strata (1-92) and offshore strata (1-14, 16, 19, 20, 23, 25, and 61-76) during 1982-2008 for ages 0-3 and 4+.

Year	0	1	2	3	4+
1982	74.28	26.52	7.54	0.50	0
1983	341.34	83.41	13.43	2.29	0.03
1984	287.43	43.91	13.23	3.17	0.00
1985	281.25	80.31	11.85	2.28	0.09
1986	140.48	27.94	11.49	1.99	0.32
1987	77.32	29.95	6.54	0.22	0
1988	275.32	20.96	12.70	0.10	0
1989	329.46	47.26	14.85	0.92	0
1990	320.81	32.93	3.77	1.02	0
1991	163.50	19.94	3.65	0.34	0
1992	223.30	9.42	4.39	0.10	0
1993	192.53	49.56	9.49	0.83	0
1994	462.33	21.98	9.40	1.46	0.02
1995	45.63	41.67	24.13	0.08	0
1996	63.56	17.31	4.00	0.27	0
1997	231.46	16.92	2.51	0.14	0
1998	149.78	48.64	8.26	0.74	0
1999	226.15	15.28	2.09	0.03	0
2000	164.44	41.94	4.98	0.38	0
2001	62.60	14.81	8.53	0.22	0
2002	88.12	10.99	3.15	0.11	0
2003	178.35	12.78	1.68	0.40	0.21
2004	66.56	16.26	8.04	0.69	0.49
2005	45.68	5.23	1.71	0.81	0.02
2006	154.96	19.78	5.25	0.93	0.08
2007	39.12	13.76	1.94	0.02	0
2008	123.06	7.69	1.09	0.06	0
2009	158.31	20.06	3.88	0.17	0.01
2010	84.09	35.90	6.90	1.25	0
2011	218.26	26.86	4.76	0.42	0.06
2012	27.15	28.83	9.91	0.62	0.07

Appendix 3. Implications of model assumptions for estimates of abundance and fishing mortality (Miller and Rago 2012).

The simple models we used here have some important underlying assumptions:

1) Fish are fully selected at the same ages by the surveys and fishery.
2) All recruitment to the stock occurs at the beginning of the year.
3) The entire stock is available to the trawl survey.

These three assumptions are not likely to apply to the actual butterfish stock, but these inconsistencies will affect the results in predictable ways. When the first assumption does not hold and the fishery selects younger fish on average than the survey, then survey efficiency is effectively lower and actual fishing mortalities would be less than those implied by the second model that does not require a fishing mortality assumption. Conversely, if the fishery selects older fish on average, the fishing mortality rates would be greater than those provided by the model.

Butterfish are likely to recruit to the fishery over some period of the calendar year and this violation of assumption 2 would cause all annual fishing mortality rates provided by the model to be greater than actual values. Assumption 3 is violated when only a fraction of the stock is available to the survey. In these instances effective efficiency would be even less than that assumed and model-based fishing mortality rates would be greater than the actual values. Therefore, violating the latter two assumptions would likely lead to over-estimation of fishing mortality rates which makes the results of the model conservative and current catches levels would be even less likely to exceed candidate reference points over a broad range of assumptions.