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An Illustrative Assessment for Northern Shrimp in NAFO Divisions 3LNO from a Surplus Production Model using Bayesian Estimation's

By

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Introduction

Northern Shrimp (*Pandalus borealis*) found upon the Grand Banks, NAFO Div. 3LNO extend beyond Canada's 200 Nmi limit and therefore are regulated by NAFO (Fig. 1). The status of this resource was initially determined from data collected during annual Canadian multi-species bottom trawl surveys that began during fall (1996) and spring (1999), as well as, commercial catches that began during 1993 (Table 1). The resource increased until 2003, remaining high until 2008. While the resource status was positive over this period, the strictly increasing data and short time series made it impossible to apply quantitative models during 2005 and 2007. However, Scientific Council within NAFO were able to determine a proxy for B_{Lim} within its Precautionary Approach (PA) Framework as the point at which a valid index of stock size declines by 85% from the maximum observed index level (19,330 t) for Northern Shrimp in Div. 3LNO (SCS Doc 04/12, Orr and Sullivan, 2013). Unfortunately there are no proposed proxies for fishing mortality reference points for this stock.

Since 2008, both the research survey biomass and commercial catch rates have been decreasing which may allow the formation of quantitative assessment and management models. Millar and Meyer (2000) provides the basis for use of Bayesian state-space modeling as an exercise that is being used to assess stock status as well as make predictions. Hvingel and Kingsley (2006) and Hvingel (2006a) have used surplus production models using Bayesian inferences, to assess shrimp off Western Greenland and in the Barents Sea (Hvingel, 2006b). Hvingel and Orr (2011) made initial use of this model to provide an integrated assessment framework and management scheme for Northern Shrimp found within the Canadian Shrimp Fishing Area (SFA) 6. This methodology has been used to try to obtain an analytical assessment for Northern Shrimp in NAFO divisions 3LNO. At previous meetings of the NAFO-ICES Pandalus Assessment Group (NIPAG) 2011 and 2012 various data inputs and priors have been investigated to understand data sensitivities for this stock.

This report investigates the effect of providing more informative priors on survey catchabilities (q) and Maximum Sustainable Yield (MSY), while relaxing the prior on Carrying capacity (K). An additional formulation constrained the relative biomass (B_t/B_{MSY}) not to exceed 2.5 in any iteration of the model runs. Although the various formulations were considered to capture the overall dynamics of the stock, it was not accepted for stock projections or risk analysis and was considered to be an illustrative assessment for this stock.

Methodology

As indicated within Table 1, this project made use of catch data provided by Contracting Party, NAFO Statlant 21A and B and monthly provisional catch tables, as well as, fishable biomass indices provided by Canadian Fisheries and Oceans spring and fall multi-species research surveys. These research surveys, using a Campelen 1800 shrimp trawl, have been conducted onboard the Canadian Coast Guard vessels Wilfred Templeman, Teleost and Alfred Needler since 1996. Details of the survey design and fishing protocols are outlined in Brodie, (1996), Brodie and Stansbury (2007), as well as McCallum and Walsh (1996).

The methodology and data selection criteria for the calculation of the fishable biomass indices from both the Canadian spring and fall surveys are outlined in Orr and Sullivan, 2013.

The surplus production model used for this report is similar to the well-defined model provided in both Hvingel and Kingsley (2006), as well as Hvingel and Orr (2011). The difference is that the present model makes use of only fishery independent data from Canadian fall and spring surveys, rather than commercial catch rate data provided in Hvingel and Orr (2011). Figure 2 provides the survey estimates standardized to their mean values along with the reported catch time series.

State equations

As noted within Hvingel and Orr (2011) the equation describing the state transition from time t to t+1 was a discrete form of the logistic model of population growth including fishing mortality (e.g. Schaefer (1954), and parameterised in terms of *MSY* (Maximum Sustainable Yield).

(1) $$B_{t+1} = B_t - C_t + 4MSY\frac{B_t}{K}\left(1-\frac{B_t}{K}\right)$$

Where *K* is the carrying capacity, or the equilibrium stock size in the absence of fishing. B_t is the stock biomass in year t. C_t is the catch taken by the fishery in year t.

To cancel out the uncertainty of the “catchability” (the parameter that scales biomass indices to real biomass) equation (1) was divided throughout by B_{MSY}, (Hvingel and Kingsley, 2006). Finally a term for the process error was applied and the state equation took the form:

(2)

$$P_{t+1} = (P_t - C_t/B_{MSY} + ((2MSY\ P_t)/\ B_{MSY})\ (1\text{-}P_t/2)) * \exp(\upsilon_t)$$

where P_t is the stock biomass relative to biomass at MSY (P_t=B_t/B_{MSY}) in year t. This frames the range of stock biomass (P) on a relative scale where P_{MSY}=1 and K=2. The 'process errors', v, are normally, independently and identically distributed with mean 0 and variance σ_{υ}^{2}. The inclusion of process error is to account for processes that are not included explicitly in the model.

Observation Equations

The model inputs are from two survey series of fishable biomass indices and one series of shrimp catches (Table 1) along with the priors given in table 2. The two series of shrimp fishable biomass indices were the fall (1996 – 2012) and the spring (1999 – 2012) Canadian trawl-surveys. The model assumes tacitly that the age structure of the population does not change, even as the population itself is changing. The fishable biomass indices were scaled to true biomass by Catchability parameters, q_{fall} and q_{spring}. Lognormal observation errors, ω and ε were applied, giving:

(3)

$$\text{Fall survey}_t = q_{fall} * B_{MSY} * P_t \exp(\omega_t)$$

$$\text{Spring survey}_t = q_{spring} * B_{MSY} * P_t \exp(\varepsilon_t)$$

The error terms, ω and ε are normally, independently and identically distributed with mean 0 and variance σ_{ω}^{2} and σ_{ε}^{2}.

Model formulation and Priors

The prior distributions are presented in Table 2. There are two formulation or Runs presented. Both Runs have the same model inputs described above but differ on the priors. The prior on carrying capacity (*K*) although having the same mean, the level of precision was greater in Run 2. The mean value of *K* was scaled (~30%) from the estimated value from the *K* of the West Greenland stock. The other informative priors, uncertainty of the survey data series, were given a gamma distribution prior with a 95% range of 10 – 30%, as used in Hvingel and Orr (2011) which are thought to be the typical range for such data . However, the prior on process error suggests a much higher process error than that used in Hvingel and Orr. These informative priors are the same for both runs, whereas the reference priors (low-information priors) on MSY and survey q's varied between the two runs to check the sensitivity of the model to these priors. Run 1 allows for a broader range on the prior for Maximum Sustainable Yield (MSY) than used in Run 2. Also q was allowed to go beyond one in Run 2. Another difference between the two runs is that Run 1 had no constraint on the modeled P_t ,while in Run 2, P_t could not exceed 2.5.

The reference priors were given when there was little or no information on the parameters to be estimated

The model was implemented in WinBugs1.4 making use of the model specification tool to check the model, include and compile the data, as well as load initial data values. The update tool was used to identify the number of updates, number of samples to thin and the refresh level. The updates are the Monte Carlo Markov Chain (MCMC) being requested while thin is the selection of k^{th} samples where k is the value of thin. This is used to reduce the autocorrelation in the simulations. In this case, an update of 1000, a thin of 100 and a Begin value of 500 would result in (100 X 1000)-500 = 99,500 iterations.

Run 1 collected the model results starting at iteration 2,000 and had a total number of 40,002 iterations to be used in determining the posterior distribution while Run 2 started at 501 and had a total number of 21,500 iterations. Each model run output was collected at a separation greater than 100 (thin = 100) to reduce the possibility of autocorrelation between values. A high number of iterations allowed statistics and the posterior distribution plot to be created reasonably.

Results

Figure 3 and 4 illustrates the model output (Run 2) as it relates to the observed fall and spring biomass indices respectively. The observed survey biomass clearly fit within the 95% credible intervals The model follows the spring and fall survey fishable biomass as they increased until 2007 and then followed it down since. Both these figures and table 3 indicate that the fall model fits closely to the fall survey estimates with the greatest difference being 32% during 2010 and no yearly trend in the residuals. However, the spring values indicate that there are relatively high differences between the model and the input data. Spring survey residuals are as high as 63% in 2001 and all residuals are positive after 2006. The model under estimated the survey during the decline, see residuals lower panel figure 4 and table 3.

Prior and posterior distribution plots are presented in figure 5. It is important to note that the prior on K was an informative prior and the posterior distribution is very similar. The other prior distributions differ from the posterior distributions and therefore suggest that there was information in the data to estimate these parameters.

Table 4 provides a summary of the parameter estimates for both formulations (Run 1&2) of the surplus production model. The estimates for most of the parameters are similar for both runs with the exceptions of the relative biomass ($P_{i} = B_t/B_{MSY}$) having lower median values in Run 2, the constrained model. Also, the survey q’s are higher in the constrained model.

The F ratio (F_t/F_{msy}) estimates are higher in Run 2 and the first estimate of $F_t > F_{msy}$ was in 2006, three year before Run 1 (table 5). The F ratio’s in the last 4 years, the period of decline, for both runs were greater than 1 with long tailed distributions (97.5 percentile > 5).

Figure 6 illustrates the result of constraining the relative biomass to 2.5. The posterior distribution is truncated in years that have a high probability of $P_t > 2.5$ (2007) and has little to no effect for years with low biomass (2012).

PA Plots: In both cases the median values were used to plot the PA graph with relative fishing mortality (F_t/ F_{MSY}) and relative biomass P_t (Figure 7). In Run 2 (Table 6) the relative biomass does not reach 2 or K whereas the unconstraint Run has it exceeds 2.5 in 2007. The constraint resulted in a reduction in the range of the relative biomass, along with a change in distribution pattern that resulted in almost 30% reductions in relative biomass estimates and almost 40% increases in relative F (Figure 7) compared to Run 1. The terminal year estimates of relative biomass are 0.46 and 0.33 in Run 1 and Run 2 respectively (Table 3&6).

The spring and fall survey catch abilities were .88 and .81 in Run 1 respectively, and estimated to be above 1 in Run 2 when the prior on the q's were widen, along with the constraint on P_i.

Annual process error was only investigated after the relative high model estimates for the process error was realized in Run 1. Results were not available prior to the end of the meeting and are not reported here. There is little improvement in the magnitude of the process error in Run 2 (33%) vs Run 1 (34%).

Conclusions

Although the various formulations were considered to capture the overall dynamics of the stock NIPAG did not accept the surplus production model for stock projections or risk analysis because of concerns over the relative magnitude of the process error and its possible serial correlation. There were also concerns over the long right tailed distributions of the relative fishing mortality (F_t/F_{MSY}) and to a lesser degree the relative high estimates of the survey catch abilities. Given these concerns the model output from Run2 was considered to be an illustrative assessment only for this stock.

The PA plot (Figure. 8) shows that the population increased steadily from 1995 to 2007 to a level of 1.8 times its MSY level while fishing below F_{msy}. Since 2007, this stock has been fished above the fishing mortality limit of F_{msy} while the population declined. The current estimate for 2012 is now considered at B_{lim} which is $0.3B_{msy}$ (Hvingel and Orr, 2011). The relative F_{2012} estimate (the terminal year) is poorly estimated as indicated by the large inter-quartile interval. The model indicates that the population experienced an average annual growth of 27% during the increase period, 1995 to 2007, and an average of 29% decline since.

The process error is larger than the observation error and this lead to the rejection of the model for projections and risk analysis. In future modeling exercises one should investigate the pattern in the annual process error. Knowledge about the stock can be gained by examining if there is serial correlation in the process error. If so, one can take advantage and have it defined explicitly in the model. However, another take on the larger process error, is that this stock cannot be properly described by constant production parameters without changes made to the model.

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Table 1. Model input data series including the total catch taken by Canadian and International shrimp fishers (1993 – 2012) as well as the fishable biomass indices from Canadian research surveys taken both during the fall (1996 – 2012) and spring (1999 – 2012).

Year	Catch	Fall	Spring
1993	1.80	NA	NA
1994	1.90	NA	NA
1995	0.00	NA	NA
1996	0.20	14.30	NA
1997	0.50	34.43	NA
1998	0.60	47.22	NA
1999	0.80	42.49	40.88
2000	4.70	80.44	80.54
2001	10.70	175.08	67.35
2002	7.00	159.88	113.67
2003	13.10	169.75	155.45
2004	13.50	NA	82.76
2005	14.40	179.92	116.59
2006	25.80	173.77	161.69
2007	23.90	239.72	264.99
2008	27.70	206.39	187.97
2009	28.50	95.04	100.58
2010	20.60	57.89	113.37
2011	14.05	61.52	56.28
2012	10.11	31.71	47.42

Table 2. The models used the following prior information where ~ denotes “distributed as..”, dunif = uniform, dlnorm = lognormal, dnorm = normal, dgamma = gamma distributed:

Parameter	Type	Run 1	Run 2
MSY	Reference	~dunif(1,100)	~dunif(1,50)
K	Informative	~dlnorm(5.33,10)|(.00,1.E4)	~dlnorm(5.33,40)|((0.001,1.E3)
q_f (fall survey catchability)	Reference	$\ln(q_f)$ ~ dunif(-10,1)	$\ln(q_f)$ ~ dunif(-10,2)
q_s (spring survey catchability)	Reference	$\ln(q_s)$ ~ dunif(-10,1)	$\ln(q_s)$ ~ dunif(-10,2)
P_{1993} (initial biomass ratio)	Informative	~dnorm(0.2, 20)|(.01,3)	~dnorm(0.2,20)|(.01,2.5)
$1/\sigma_f^2$ (Precision of fall survey)	Informative	~dgamma(4,0.1125)	~dgamma(4,0.1125)
$1/\sigma_s^2$ (Precision of spring survey)	Informative	~dgamma(4,0.1125)	~dgamma(4,0.1125)
$1/\sigma_p^2$ (Precision of model)	Reference	~dgamma(1,.1)	~dgamma(1,.1)

Table 3. Observed fishable biomass indices from the fall and spring surveys with their respective model estimates from Run 2 along with the residuals (% of observed value).

year	fall survey fishable biomass (000 t)	fall survey model estimate (000 t)	percent difference
1996	14.30	17.75	-24.13
1997	34.43	31.64	8.10
1998	47.22	43.83	7.18
1999	42.49	48.08	-13.16
2000	80.44	81.99	-1.93
2001	175.08	123.80	29.29
2002	159.88	142.50	10.87
2003	169.75	159.20	6.22
2004		125.00	
2005	179.92	157.50	12.46
2006	173.77	180.40	-3.82
2007	239.72	222.70	7.10
2008	206.39	187.50	9.15
2009	95.04	107.00	-12.58
2010	57.89	76.35	-31.89
2011	61.52	58.63	4.70
2012	31.71	40.62	-28.10

year	spring survey fishable biomass (000 t)	spring survey model estimate (000 t)	percent difference
1999	40.88	44.31	-8.39
2000	80.54	75.03	6.84
2001	67.35	109.9	-63.18
2002	113.67	129.4	-13.84
2003	155.45	144.8	6.85
2004	82.76	112.6	-36.06
2005	116.59	142	-21.79
2006	161.69	164.3	-1.61
2007	264.99	204.2	22.94
2008	187.97	170.8	9.13
2009	100.58	98.53	2.04
2010	113.37	71.68	36.77
2011	56.28	54.14	3.80
2012	47.42	37.91	20.05

Table 4. Parameter estimates from both model formulations: mean, standard deviation (sd) and 25, 50, and 75 percentiles of the posterior distribution of selected parameters.

Run 1

Parameter est.	mean	sd	MC error	25.00%	median	75%
MSY	16.86	8.216	0.1111	11.1	16.12	21.73
K	209.6	33.66	0.6529	185.6	206.7	230.5
r	0.3251	0.1541	0.002216	0.2151	0.3155	0.422
q fall survey	0.9717	0.429	0.01714	0.6698	0.879	1.196
q spring survey	0.8924	0.3971	0.01574	0.6141	0.8076	1.096
P_1 = 1993	0.205	0.1035	0.00202	0.1294	0.1725	0.2473
P_{14} = 2007	2.76	1.278	0.04935	1.92	2.564	3.277
sd fall survey	0.213	0.0543	4.83E-04	0.174	0.2067	0.2453
sd spring survey	0.274	0.0585	4.01E-04	0.2324	0.2674	0.3079
Process error	0.3449	0.0816	8.63E-04	0.2878	0.3346	0.3909
B_{MSY}	104.8	16.83	0.3265	92.82	103.3	115.2
F_{MSY}	0.1818	9.52E-02	0.001316	0.1138	0.1717	0.237
P_{20} = 2012	0.4981	0.2324	0.00871	0.3399	0.4623	0.6037

Run 2

Parameter est.	mean	sd	MC error	25.00%	median	75.00%
MSY	16.81	7.275	0.09528	11.85	16.15	20.98
K	207	32.34	1.166	184.2	204.5	227.1
r	0.3298	0.1419	0.001713	0.2314	0.3215	0.4158
q fall survey	1.301	0.4209	0.02524	0.987	1.212	1.548
q spring survey	1.193	0.3912	0.0232	0.9007	1.113	1.42
P_1=1993	0.1747	0.07721	0.001719	0.12	0.1493	0.203
P_{14}=2007	1.48E+00	0.4039	0.02135	1.176	1.472	1.771
sd fall survey	0.213	0.0513	9.44E-04	0.1747	0.2062	0.2438
sd spring survey	0.278	0.0586	7.49E-04	0.2358	0.2705	0.3115
Process error	0.3311	0.0824	0.001394	0.2729	0.3201	0.3764
B_{MSY}	103.5	16.17	0.5831	92.1	102.3	113.6
F_{MSY}	0.184	8.80E-02	0.001054	0.123	0.1752	0.2331
P_{20}= 2012	0.3438	0.1165	0.005789	0.2572	0.331	0.4157

Table 5. Relative F (F_t/F_{MSY}) estimates from the surplus production model for Runs 1 and 2.

Run 1

Year	mean	sd	MC error	25.00%	Median	75.00%
1993	0.765	0.7078	0.006314	0.4061	0.5992	0.88
1994	0.8485	8.48E-01	0.007683	0.4178	0.6396	0.9838
1995	0	0.00E+00	2.57E-13	0	0	0
1996	0.08637	9.30E-02	0.001165	0.04018	0.06199	0.09888
1997	0.1203	0.1263	0.001711	0.05545	0.08639	0.1404
1998	0.1048	1.11E-01	0.001517	0.04811	0.07518	0.1219
1999	0.1271	0.1355	0.001817	0.05881	0.09114	0.1466
2000	0.4367	0.4602	0.006206	0.2023	0.3142	0.5062
2001	0.6734	0.7134	0.009682	0.3101	0.4834	0.7847
2002	0.3751	0.3936	0.005412	0.173	0.269	0.4364
2003	0.6268	0.6602	0.008998	0.2884	0.4493	0.7281
2004	0.8486	0.9126	0.01162	0.3967	0.6079	0.9731
2005	0.7038	0.7325	0.009942	0.3292	0.5068	0.815
2006	1.083	1.131	0.01496	0.5115	0.7826	1.251
2007	0.785	0.8248	0.01142	0.3619	0.5596	0.9112
2008	1.109	1.16	0.0161	0.5116	0.7952	1.295
2009	2.021	2.101	0.02747	0.9593	1.467	2.334
2010	2.025	2.143	0.02853	0.9376	1.461	2.351
2011	1.803	1.901	0.02628	0.8306	1.293	2.099
2012	1.899	2.132	0.02869	0.8389	1.325	2.19

Table 5 continued. Relative F (F_t/F_{MSY}) estimates from the surplus production model for Runs 1 and 2.

Run 2

Year	mean	sd	MC error	25.00%	median	75.00%
1993	0.8099	0.6712	0.00691	0.4721	0.6705	0.944
1994	0.9572	8.97E-01	0.01119	0.512	0.7589	1.116
1995	0	0.00E+00	6.82E-13	0	0	0
1996	0.1082	1.07E-01	0.0018	0.05562	0.0827	0.1241
1997	0.1534	0.1456	0.00258	0.07905	0.1187	0.1773
1998	0.134	1.28E-01	0.00232	0.06879	0.103	0.1558
1999	0.1614	0.1576	0.00279	0.08301	0.1231	0.1842
2000	0.5559	0.5283	0.00954	0.2887	0.4293	0.6381
2001	0.8579	0.8258	0.01488	0.4377	0.6592	0.991
2002	0.4794	0.4586	0.00826	0.2458	0.369	0.5539
2003	0.8032	0.7649	0.01398	0.4118	0.6192	0.9288
2004	1.058	1.052	0.01838	0.5392	0.7997	1.219
2005	0.8943	0.8608	0.01516	0.4638	0.6865	1.031
2006	1.377	1.297	0.0227	0.7241	1.064	1.569
2007	1.032	0.9647	0.01613	0.5438	0.7976	1.183
2008	1.432	1.339	0.02353	0.7455	1.106	1.652
2009	2.548	2.424	0.04114	1.356	1.975	2.916
2010	2.576	2.445	0.04263	1.339	2.004	2.969
2011	2.317	2.195	0.03993	1.195	1.797	2.686
2012	2.447	2.483	0.04563	1.203	1.827	2.837

Table 6. Relative biomass (B_t/B_{MSY}) estimates from the surplus production model for Runs 1 and 2.

Run 1

Year	mean	sd	MC error	25.00%	median	75.00%
1993	0.205	0.1035	0.00202	0.1294	0.1725	0.2473
1994	0.206	0.1155	0.002656	0.1296	0.1751	0.2479
1995	0.2028	0.1121	0.003092	0.1286	0.1768	0.2458
1996	0.2106	0.09685	0.003476	0.1462	0.1936	0.2516
1997	0.3796	0.1798	0.006774	0.2597	0.3482	0.4544
1998	0.5249	0.2498	0.00941	0.3577	0.4819	0.628
1999	0.5699	0.2559	0.009851	0.3978	0.5314	0.6812
2000	0.9737	0.4428	0.01718	0.6786	0.9041	1.162
2001	1.455	0.6956	0.02614	0.9967	1.334	1.74
2002	1.697	0.7896	0.03034	1.177	1.574	2.021
2003	1.904	0.8848	0.03405	1.316	1.761	2.268
2004	1.444	0.6725	0.02393	1.004	1.331	1.72
2005	1.844	0.841	0.03224	1.291	1.711	2.189
2006	2.122	0.9424	0.03633	1.507	1.982	2.502
2007	2.76	1.278	0.04935	1.92	2.569	3.277
2008	2.271	1.061	0.04091	1.564	2.104	2.705
2009	1.257	0.5621	0.02161	0.8852	1.167	1.488
2010	0.9259	0.4347	0.01643	0.6349	0.8514	1.108
2011	0.7096	0.3314	0.01284	0.488	0.6576	0.8476
2012	0.4981	0.2324	0.00871	0.3399	0.4623	0.6037

Table 6 continued. Relative biomass (B_t/B_{MSY}) estimates from the surplus production model for Runs 1 and 2.

Run 2

Year	mean	sd	MC error	25.00%	median	75.00%
1993	0.1747	0.07721	0.001719	0.12	0.1493	0.203
1994	0.1637	0.07656	0.002037	0.1132	0.1464	0.194
1995	0.1511	0.06598	0.002194	0.1058	0.1382	0.1821
1996	0.1503	0.05044	0.002315	0.1139	0.1439	0.1789
1997	0.2621	0.08092	0.004043	0.2022	0.2558	0.3133
1998	0.3619	0.1137	0.005676	0.2778	0.3529	0.4346
1999	0.3991	0.1201	0.006214	0.3085	0.392	0.4778
2000	0.6762	0.1986	0.01037	0.5277	0.6649	0.808
2001	1.009	0.3147	0.0156	0.7769	0.9866	1.216
2002	1.175	0.3513	0.01818	0.9133	1.152	1.41
2003	1.311	0.3876	0.02023	1.017	1.287	1.574
2004	1.04	0.3431	0.01565	0.7879	1.005	1.254
2005	1.289	0.376	0.0193	1.009	1.273	1.545
2006	1.481	0.4039	0.02135	1.176	1.472	1.771
2007	1.813	0.4398	0.02376	1.479	1.855	2.188
2008	1.537	0.4263	0.02251	1.211	1.522	1.85
2009	0.8853	0.2542	0.01296	0.6955	0.8698	1.051
2010	0.6398	0.1972	0.009784	0.4931	0.6211	0.7639
2011	0.4862	0.1461	0.007623	0.3761	0.4761	0.5835
2012	0.3438	0.1165	0.005789	0.2572	0.331	0.4157

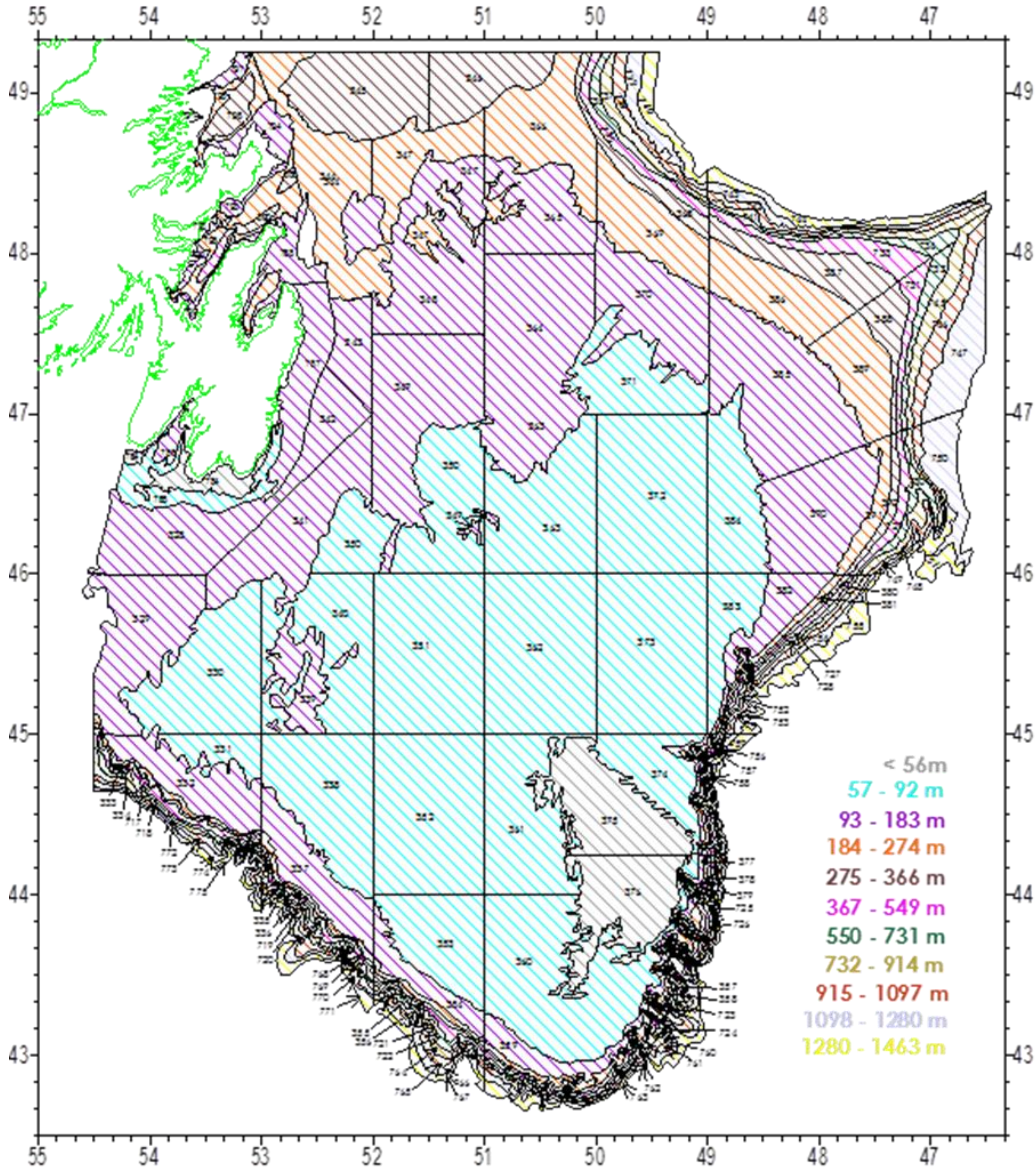


Figure 1. The NAFO Divisions 3LNO stratification scheme used in the Canadian multi-species research bottom trawl survey set allocation (G. Cossitt)

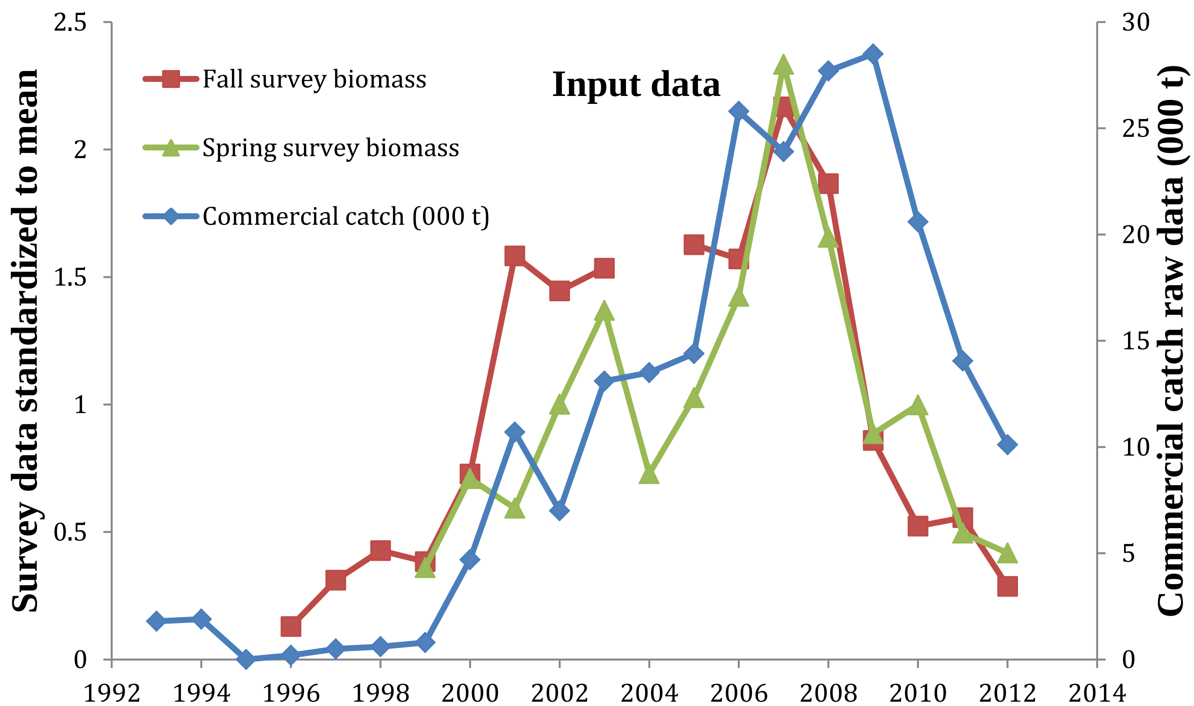


Figure 2. Model input data standardized to mean values for each survey series along with the recorded total commercial catch

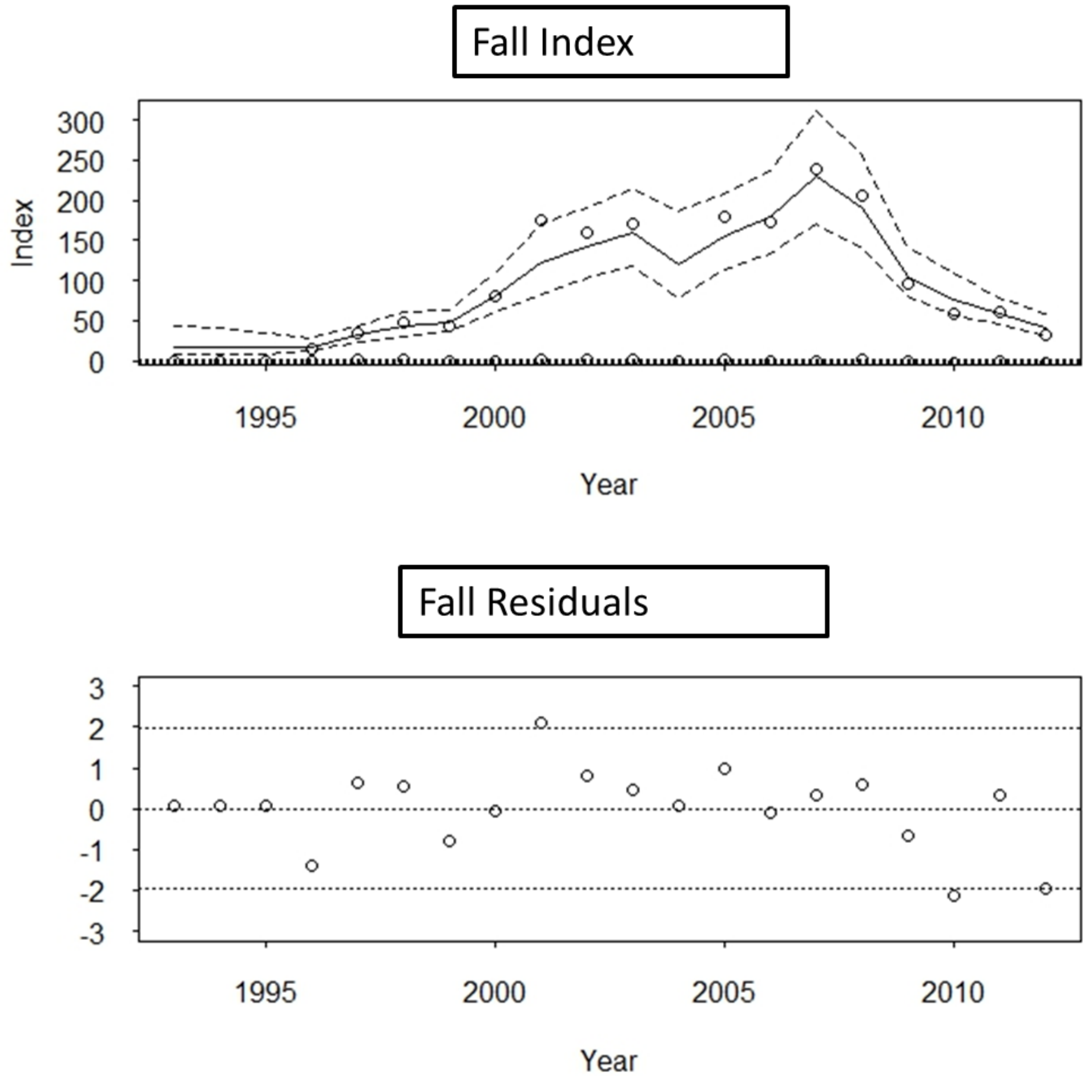


Figure 3. Top panel: Fishable biomass index from the Canadian fall survey and model output with 95 credible interval with the residuals in the lower panel.

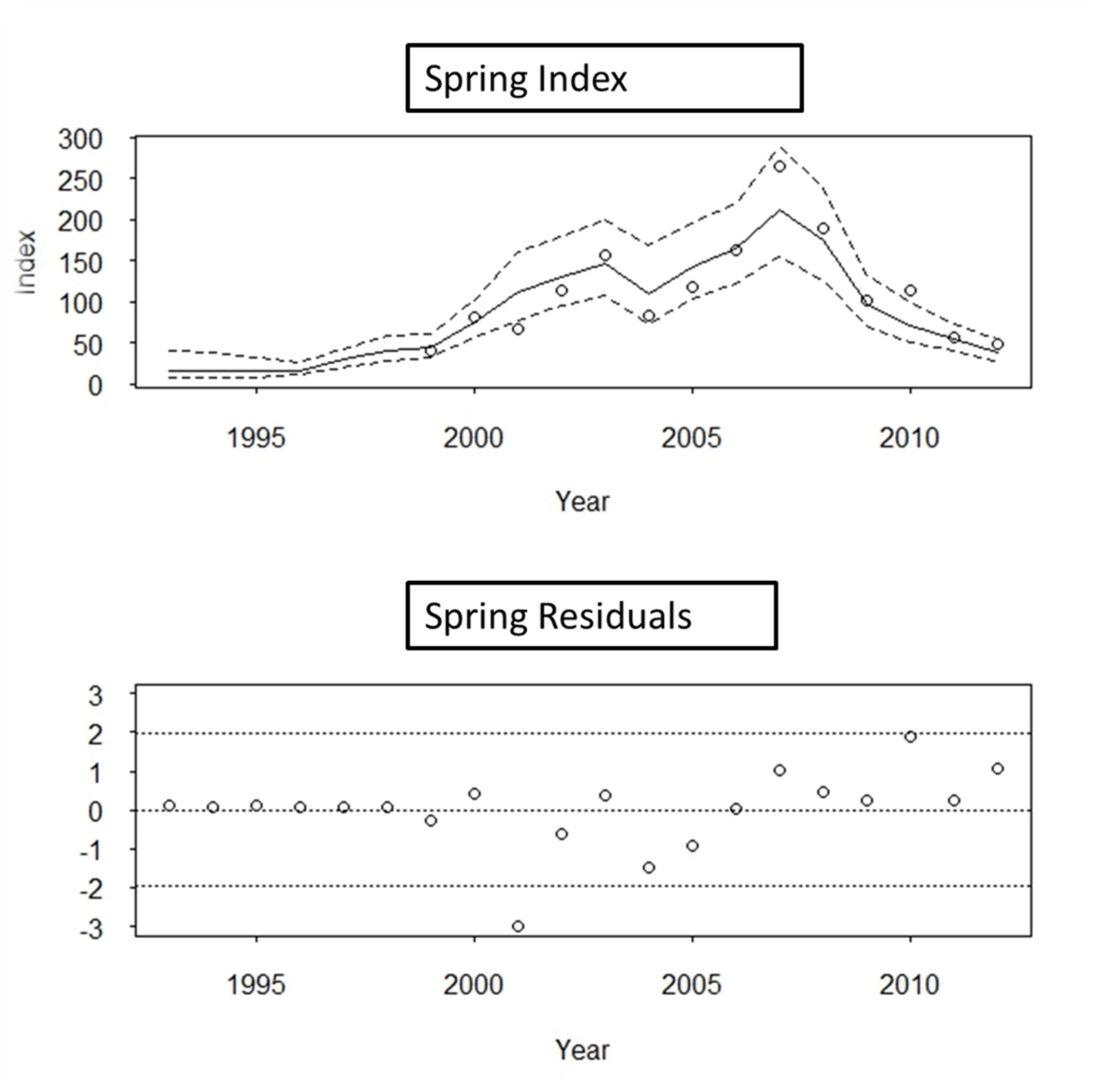


Figure 4. Top panel: Fishable biomass index from the Canadian spring survey and model output with 95 credible interval with the residuals in the lower panel.

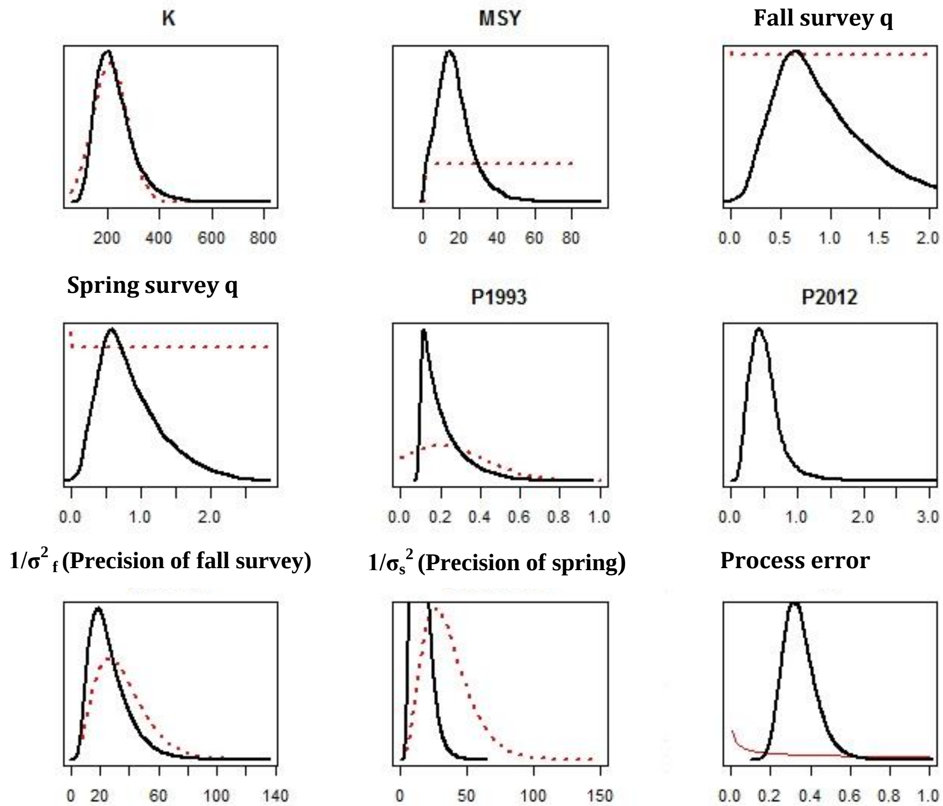
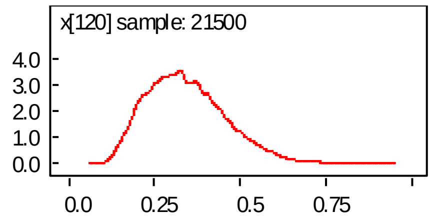
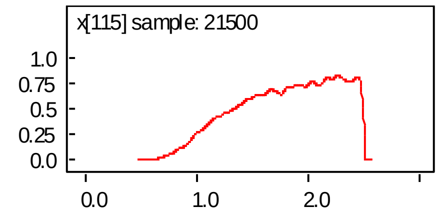


Figure 5. Probability density distributions of model parameters: prior (red dots) and estimated posterior (solid line).

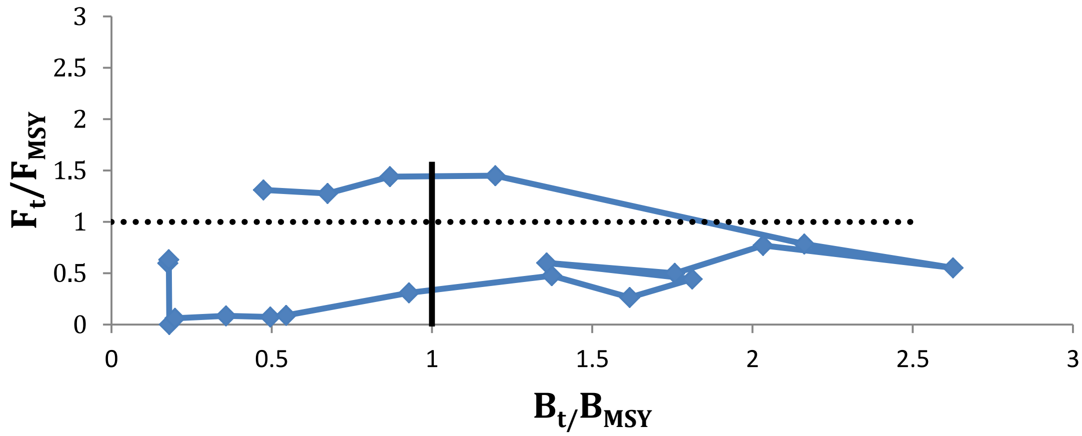


B_{2012}/B_{MSY}

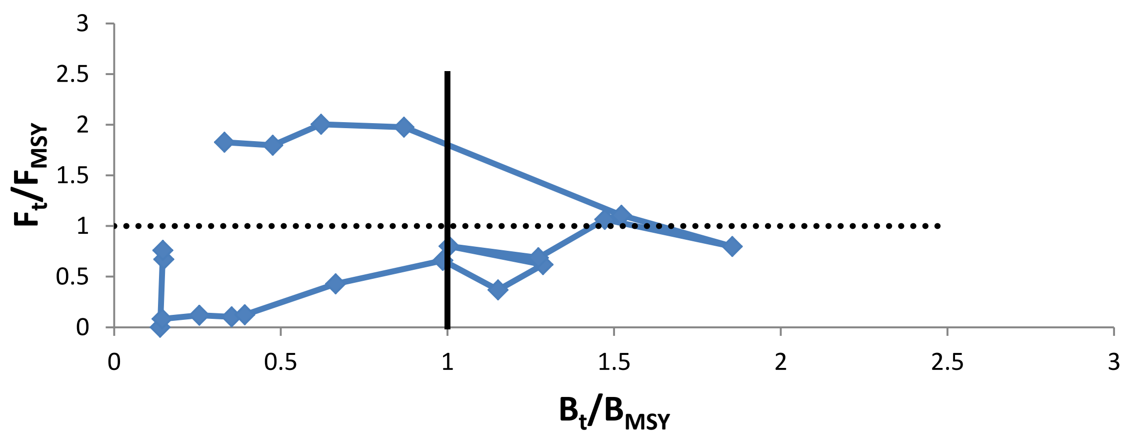


B_{2007}/B_{MSY}

Figure 6. Posterior distribution of biomass-ratio (B/B_{MSY}) from Run 2 for years 2012 (terminal year) and 2007 (year with the maximum biomass). The estimate for 2007 clearly illustrates the truncation caused by the biomass ratio constraint of 2.5.



Run 1



Run 2

Figure 7. estimated annual median biomass-ratio (B/BMSY) and fishing mortality-ratio (F/FMSY) 1993 - 2012. Run 2 was constrained with a biomass ratio of 2.5 in any year.

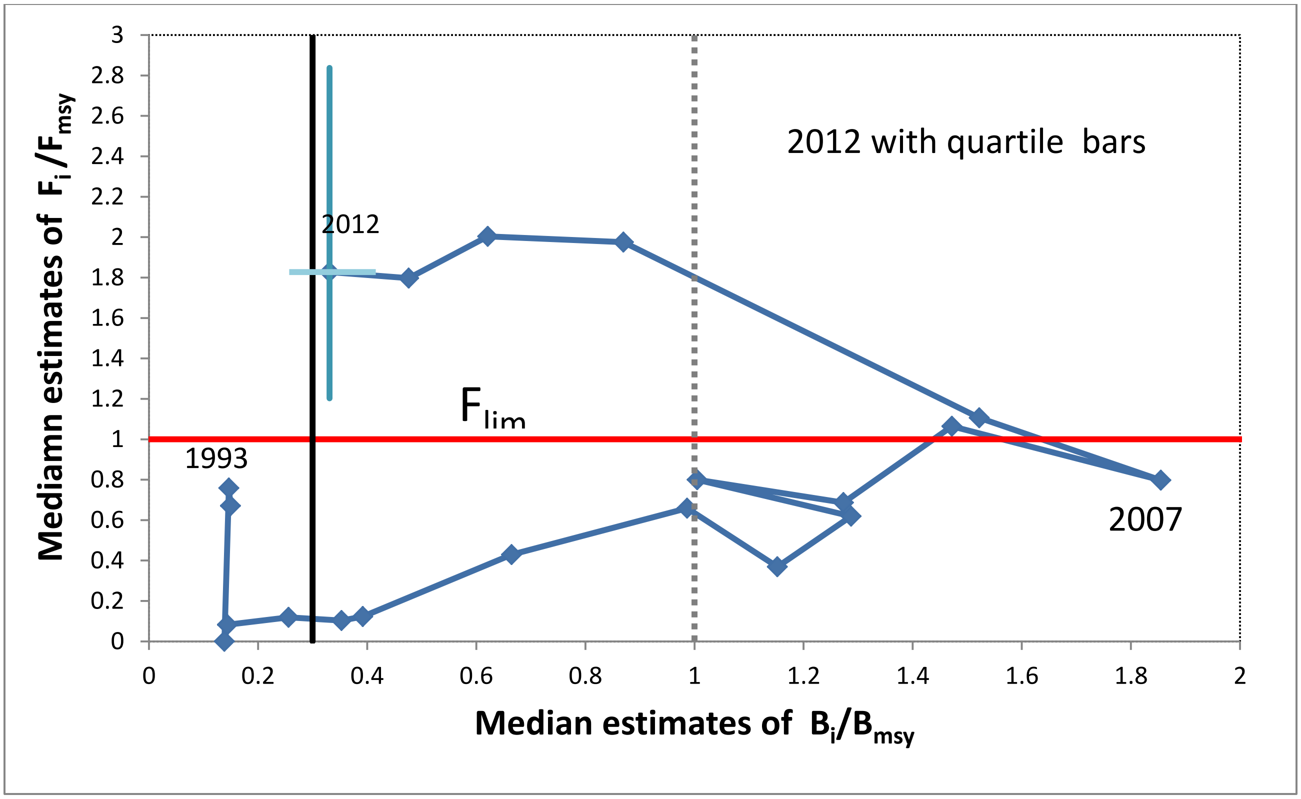


Figure 8 . PA plot as realized by Run 2: estimated annual median biomass-ratio (B/BMSY) and fishing mortality-ratio (F/FMSY) 1993 - 2012. The reference point for stock biomass, Blim and fishing mortality are indicated by the solid black and red lines respectively. Error bars are inter-quartile range