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Limit reference points for Div. 3LNO Thorny Skate (*Amblyraja radiata* Donovan, 1808) and Div. 3NOPs White Hake (*Urophycis tenuis*, Mitchill 1815)

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ABSTRACT

In 2004, the NAFO Fisheries Commission adopted a Precautionary Approach Framework (PAF) to guide fisheries management decision making, including guidelines for deriving biological reference points, such as B_{lim}, to be used in evaluating and monitoring the status of fish and shellfish stocks. Limit reference points have not yet been developed for White Hake in 3NOPs and Thorny Skate in 3LNO. A variety of approaches for estimating B_{lim} were explored, including Bayesian Surplus Production, Catch-resilience, and ASPIC models. Empirical reference points based on proxies for B_{MSY} were also considered. Further work is required to derive satisfactory limit reference points for these two stocks.

INTRODUCTION

The objective of this paper is to assess various approaches to the estimation of biological reference points for NAFO Divisions 3LNO Thorny Skate and Div. 3NOPs White Hake (Fig. 1). In the absence of accepted analytical assessments for these stocks, precautionary limit reference points have not been previously estimated.

In this paper, different approaches to the estimation of limit reference points were investigated. These include Bayesian surplus production modeling (for White Hake), and ASPIC (Prager 1994, 2014) surplus production modeling (for Thorny Skate). For Thorny Skate and White Hake, Catch- resilience models (Martell and Froese 2013), and empirical reference points (based on Canadian research survey indices) were investigated.

Bayesian Model

Simpson *et al*. (2015) developed a Bayesian state-space implementation of the Schaefer Surplus-Production model (Schaefer 1954) for Div. 3NOPs White Hake following the approach used by Bailey (2012) for American Plaice (*Hippoglossoides platessoides*). Population dynamics of White Hake were modeled using Canadian and EU-Spain spring research surveys, NAFO-reported commercial landings (1960-2013), and an original set of estimated priors for K, r, and q (Table 1). Models were evaluated based on posterior distributions of the input parameters, overall deviance information criteria (DIC), residual fits, diagnostics plots, and influence of process error on the model.

Model Results

Final model formulation was accepted based on overall deviance information criteria (DIC), model residual fits, and diagnostics plots (e.g., Kernel density estimates of posteriors, convergence of chains using sampler running means, time series trace; see Figs. 2-4, Table 2). Model process error varied without bias and was considered to be within an acceptable range (Fig. 5). In the final model, the priors specified in Table 3 were used.

Posterior results for the Bayesian surplus production models (BSP) are provided in Table 2, and modeled biomass over 1960-2013 is shown in Figure 6. Posterior distributions of sigma (process error), model deviance, K, and r are shown in Figure 7, with values provided in Table 2. As shown in Figure 7, posterior distributions of the variables were updated compared to priors; indicating that data had adjusted the priors based on available data.

Estimated catchabilities (q) for research surveys are shown in Figures 8 and 9, and posterior results are provided in Table 3. In all cases, catchability had shifted from the original uninformative priors.

B_{MSY}, MSY, and F_{MSY} are shown in Figure 10, with values provided in Table 3. These estimates are calculated based on the posterior estimates of K and r, and show no irregularities in their distribution. The MSY for this stock is 3.5 (000s t), with a B_{MSY} of 42.3 (000s t). Given a B_{MSY} of 42.3 (000 t), a limit reference point of 30% B_{MSY} would be 12.7 (000 t). Median modeled values for fishing mortality (F) in Div. 3NOPs during 1960-2013 are shown in Figure 11. In peak periods, F remained below 0.3, but exceeded F_{MSY} (i.e., 0.1). Since the mid-to-late 2000s, F estimates have declined to values less than F_{MSY}, which corresponds to the recent period of increasing biomass.

Catch-resilience Model

The Catch-resilience model developed by Martell and Froese (2013) estimates MSY from catch data and is intended for data-poor stocks where only a time series of catch is available. The method is based on a Bayesian Schaefer model (Schaefer 1954) that characterizes biomass dynamics in terms of the intrinsic rate of increase (r) and carrying capacity (K). Overall, the method identifies values of r and K that give viable stock trajectories for the observed data, from which the applicable r-K pairs are used to derive the distribution for MSY. Catch-resilience models were run for Div. 3LNO Thorny Skate and Div. 3NO White Hake with various input parameters, to investigate the robust nature of the model estimates. Sensitivity analysis included variation in process error, range of K, final biomass, and resilience.

Model Results

Overall, the estimates of MSY for Div. 3LNO Thorny Skate and Div. 3NO White Hake were very robust to variation in process error, resilience, and final biomass (Figs. 12, 13). Final model runs are displayed in Figures 14 (Thorny Skate) and 15 (White Hake). For Thorny Skate, estimated B_{MSY} was 83 160 t, which corresponds to a B_{lim} of 24 948 t and an F_{MSY} of 0.08. For White Hake, estimated B_{MSY} was 26 093 t, which corresponds to a B_{lim} of 7 828 t and an F_{MSY} of 0.07.

ASPIC Models

Simpson *et al*. (2008) applied the ASPIC surplus production model software (ASPIC Version 5.24; Prager 1994, 2005) to commercial landings and Canadian survey biomass indices for the Thorny Skate stock. Several model formulations were explored; however, various indicators of model suitability were not accepted. Given the availability of longer time series, further ASPIC model formulations were investigated for Div. 3LNO Thorny Skate using ASPIC Version 7.01 (Prager 2014).

Model Results

ASPIC models were assessed based on the model R-squared values (on CPUE), residual patterns, correlation between biomass indices, and consideration of the estimated parameters. The model formulations and parameter estimates are illustrated in Table 4. The run that produced the best fit for Div. 3LNO Thorny Skate used observed commercial landings from 1996-2013 and Canadian spring Campelen survey data, tuned with the Canadian autumn survey Campelen data, for 1996-2013 (Table 4). This model estimated an MSY of 16 160 t, with a B_{MSY} of 42 230 t, and F_{MSY} of 0.382. It must be noted that model diagnostics were poor for all models and none are acceptable as a model of Thorny Skate in NAFO Div. 3LNO.

Empirical Methods

When a survey index is available, empirical methods based on high values, periods of high productivity or other survey data points can be used to derive a proxy for B_{MSY} from the survey index from which a Limit Reference Point is calculated. For Witch Flounder, this reference point was derived as 15% of the highest point in the survey series (Parsons 2013). For other stocks, B_{lim} has been derived as 30% B_{MSY} (Lee *et al* 2014). The default LRP under the NAFO Precautionary Approach is 30% of B_{MSY} (NAFO 2004). Alternative metrics also exist such as B_{loss}, which is the lowest point in the survey index from which the population has recovered.

Thorny Skate

For Thorny Skate, B_{MSY} proxies were derived from the Canadian Div. 3LNO spring survey using both Engel (converted to Campelen equivalents) and Campelen trawl data, as well as from the Div. 3LNOPs spring Campelen series. These proxies were then used to explore probable values for LRPs.

A proxy for B_{lim} may be the point at which a biomass index declines by 85% from its maximum observed value. The highest biomass estimate for Thorny Skate was approximately 299 112 t (Campelen equivalents; from the 1985 spring survey). A B_{lim} of 44 867 t was then calculated from this value. However, significant removals of Div. 3LNO Thorny Skate began in the late 1940s (Kulka and Mowbray 1998), and were recorded by NAFO since 1960 (Fig. 16). Therefore, this highest survey abundance estimate cannot represent B_o for this stock, so applying the 85% decline criterion to establish a LRP is not prudent in this case.

Although not representative of B_o, a high biomass estimate from the mid-1980s can constitute a benchmark, and may represent B_{MSY} for this stock.. Various proxies for B_{MSY} were calculated as geometric means (G) using: (1) the entire spring survey time-series (i.e., including Campelen equivalent estimates; 1985-2014); (2) the period of highest productivity (i.e., two successive years of high stock biomass); (3) the highest annual biomass estimate (B_{MAX}); and (4) the three highest biomass estimates. Using the calculations described above, B_{MSY} proxies ranged from 98 167 t to 299 112 t; LRP values ranged from 29 450 t to 89 734 t (Table 5; Fig. 17a). A geometric mean was chosen for estimation instead of an arithmetic average since a geometric mean will normalize the ranges being averaged, so that no range dominates the weighting on the geometric mean.

Given uncertainties with current Div. 3LNO Thorny Skate productivity, as well as any concerns with conversion factors (i.e., converting Engel trawl catches to Campelen equivalents), another approach is to use only Campelen survey data. As discussed previously, calculating B_{lim} based on 85% of the highest biomass estimate from the Campelen series cannot provide an appropriate LRP. Therefore, B_{MSY} proxies (using spring Campelen data; 1996-2014) yielded values ranging from 85 557 t to 131 617 t. LRP values ranged from 25 667 t to 39 485 t (Table 6; Fig. 17b).

Using a single-peak annual biomass estimate to derive LRPs for this stock is problematic, because: A) highest annual biomass estimates occurred at the beginning of Engel trawl use, and at the end of the Campelen period; and B) the Canadian spring survey index has a considerable degree of variability. Using a geometric mean for a period associated with high biomass, or even for an entire survey series (1985-2014), may be more appropriate. A B_{lim} of 30% of the three highest biomass years over the whole survey series would be 72 404 t (Table 5). The spring survey index declined below this level in 1993, and remained generally low; although there have been slight increases in recent years. The most recent period (2007-2014) of higher annual estimates is associated with lower reported landings which average about 5 500 t.

A B_{lim} derived from a geometric mean of the entire survey series is 29 450 t (Table 5). Using only the Campelen period (1996-2014), B_{lim} values for its three highest biomass estimates and for this entire period are 38 312 t and 25 667 t, respectively (Table 6). The spring survey index has not declined to these values.

Further investigation was done on the survey index for Thorny Skate from Div. 3LNOPs (Fig. 18). Proxies of B_{MSY} were derived by taking 1) the geometric mean of the index during 1984-1991, the same period without the very high 1985 value, and the period 1987-1991 where biomass were higher. In addition, B_{loss} which is the value in 1994, and a proxy for B_{loss},were calculated, which was the geometric mean of the index from 1993-1997, a period of low biomass. There was very little difference in any of the proposed B_{lim} reference points based upon their means (Fig. 18)

White Hake

For White Hake, empirical proxies for B_{MSY} were derived from the Canadian Div. 3NO spring survey using Campelen trawl data for 1996-2014. There is no conversion factor between Engel and Campelen time series, and the recent survey index encompassed a period of high abundance/biomass (1999-2002). Proxies of B_{MSY} from the Campelen spring survey of Div. 3NO were derived by taking 1) the highest point of the series (i.e., 2000); 2) the geometric mean of the three highest years (1999-2001); and 3) the 75th-percentile of the entire time series. The LRPs were calculated by taking 15% of the highest point, 430% of the 3-year average, and

50% of the 75-percentile. B_{lim} estimates obtained from these methods ranged from 2 389 t (based on the highest point) to 5 739 t (i.e., 30% of the 3-year average; Fig. 19).

Conclusion

A variety of approaches for estimating B_{lim} were explored, including Bayesian and ASPIC Surplus Production models, Catch-resilience models and empirical reference points. In all cases, concerns exist on the establishment of limit reference points from any of the potential methods for these particular species, based on their population characteristics and life history. In the case of white hake, the occurrence of episodic periods of high recruitment and increased population biomass creates issues in determining what constitutes "normal" years, and "high" biomass. This is also problematic for the modelling of this stock and the resulting process error. For thorny skate, given the low reproductive rate and slow growth rate, the time period over which an increase in biomass can be observed following reduced harvest rates is also an issue. At this time, further work is required to derive satisfactory limit reference points for White Hake in 3NOPs before NAFO can adopt reference points under the Precautionary Approach Framework. For Thorny Skate, while modelling attempts were not successful in establishing a B_{lim}, empirical survey estimates showed strikingly similar estimates from B_{lim} regardless of estimates using B_{MSY} proxies or B_{loss} or B_{loss} proxies.

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Table 1. Priors for parameters used in the surplus production model for Div. 3NOPs White Hake. Prior stochastic nodes for r (intrinsic rate of population growth), K (carrying capacity), and q (catchability) are also presented with 2.5% and 97.5% quantiles and the distribution used.

Parameter	Description	Prior Distribution
K	Carrying Capacity	lognormal (μ=100kt, sd=100kt); 2.5% and 97.5% quantiles at 13.83kt and 361.54kt.
r	Population growth rate	lognormal (μ=0.2, sd=0.15); 2.5% and 97.5% quantiles at 0.04 and 0.59
q.ynke	Catchability, Canadian Yankee Trawl Series	lognormal (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62
q.s.cam	Catchability, Canadian Spring Campelen Trawl Series	lognormal (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62
q.f.cam	Catchability, Canadian Fall Campelen Trawl Series	lognormal (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62
q.s.eng	Catchability, Canadian Spring Engel Trawl Series	lognormal (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62
q.f.eng	Catchability, Canadian Fall Engel Trawl Series	lognormal (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62
q.eu	Catchability, European Union Series	lognormal (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62
Sigma	Process error	Uniform (0,1)
tau.ynke	Observation error, Canadian Yankee Trawl	Uniform (0.46, 1.37)
tau.s.cam	Observation error, Canadian Spring Campelen Trawl	Uniform (0.44,1.31)
tau.f.cam	Observation error, Canadian Fall Campelen Trawl	Uniform (0.57, 1.72)
tau.s.eng	Observation error, Canadian Spring Engel Trawl	Uniform (0.65, 1.96)
tau.f.eng	Observation error, Canadian Fall Engel Trawl	Uniform (0.63, 1.89)
tau.eu	Observation error, European Union Series	Uniform (0.87, 2.62)

Table 2. Parameter estimates and Deviance Information Criteria (DIC) for models using different priors for Div. 3LNOPs White Hake. Priors for initial model are given in Table 1. Priors and posterior stochastic nodes are presented with their median and 2.5% and 97.5% quantiles.

Run	Parameter(s) Adjusted	r	K	Sigma	q.s.eng	q.s.cam
1	Initial	0.31 (0.15 – 0.51)	47.3 (30.6 – 112.5)	0.13(0.01 – 0.35)	0.57 (0.29 – 1.02)	1.25 (0.68 – 2.07)
2	Tau (0.001,CV) Eng and Cam.	0.29 (0.11 – 0.57)	51.2 (27.7 – 159.1)	0.36 (0.17 – 0.52)	0.41 (0.22 – 0.73)	1.10 (0.60 – 1.85)
3	Tau~dgamma(0.01,0.01)	0.29 (0.11 – 0.58)	50.3 (28.4 – 136.4)	0.36 (0.21 – 0.51)	0.41 (0.22 – 0.72)	1.10 (0.59 – 1.88)
4	Tau~IGamma(0.01,0.01)	0.29 (0.11 – 0.59)	50.7 (27.3 – 166.9)	0.40 (0.27 – 0.55)	0.38 (0.21 – 0.67)	1.05 (0.57 – 1.78)
5	K, mean = 50.0; 2.5% and 97.5% quantiles at 6.9 and 180.8) K~dlnorm(3.57,1.44)I(5,500)	0.32 (0.12 – 0.63)	43.4 (26.6 – 111.0)	0.40 (0.28 – 0.54)	0.39 (0.21 – 0.68)	1.07 (0.58 – 1.84)
6	r, mean=0.1, sd=0.2; 2.5% and 97.5% quantiles at 0.004 and 0.54. r ~ dlnorm(-3.11,0.62)I(0,1)	0.30 (0.05 – 0.64)	50.8 (26.9 – 162.1)	0.40 (0.27 – 0.55)	0.38 (0.21 – 0.68)	1.10 (0.59 – 1.84)
7	Sigma changed to Igamma. sigma ~ dgamma(0.01,0.01) isigma <- 1/sigma	0.30 (0.11 – 0.59)	49.5 (28.4 – 139.4)	0.15 (0.06 – 0.28)	0.38 (0.21 – 0.67)	1.07 (0.57 – 1.85)
8	r, mean=0.1, sd=0.2; r ~ dlnorm(-3.11,0.62)I(0,1) sigma ~ dgamma(0.01,0.01) isigma <- 1/sigma. Combination of runs 6 and 7.	0.29 (0.05 – 0.64)	51.1 (27.0 – 164.3)	0.16 (0.06 – 0.29)	0.38 (0.20 – 0.67)	1.04 (0.56 – 1.78)
9	As 8 but with gamma dist on q. q~dgamma(1,1)	0.17 (0.01 – 0.50)	69.6 (33.6 – 273.1)	0.14 (0.07 – 0.26)	0.21 (0.09 – 0.47)	0.61 (0.24 – 1.32)
10	As 9 but r, mean=0.2, sd=0.15; 2.5% and 97.5% quantiles at 0.04 and 0.59. r ~ dlnorm(-1.83,2.24)I(0,1)	0.23 (0.08 – 0.51)	62.2 (32.6 – 184.9)	0.14 (0.07 – 0.26)	0.24 (0.10 – 0.52)	0.68 (0.26 – 1.44)

Table 3. Summary of parameter posteriors and their priors for the White Hake surplus production model (Div. 3NOPs). Prior stochastic nodes for r (intrinsic rate of population growth), K (carrying capacity), and q (catchability) are presented with 2.5% and 97.5% quantiles and the distribution used.

Parameter	Description	Prior Distribution	Posterior
K	Carrying Capacity	lognormal (μ=100kt, sd=100kt); 2.5% and 97.5% quantiles at 13.83kt and 361.54kt.	67.0 (33.0 – 215.5)
r	Population growth rate	lognormal (μ=0.1, sd=0.2); 2.5% and 97.5% quantiles at 0.004 and 0.54	0.17 (0.01 – 0.50)
q.ynke	Catchability, Canadian Yankee Trawl Series	Gamma (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62	0.12 (0.05 – 0.28)
q.eu	Catchability, European Union Series	Gamma (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62	0.04 (0.014 – 0.10)
q.s.eng	Catchability, Canadian Spring Engel Trawl Series	Gamma (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62	0.21 (0.08 – 0.47)
q.f.eng	Catchability, Canadian Fall Engel Trawl Series	Gamma (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62	0.07 (0.02 – 0.22)
q.s.cam	Catchability, Canadian Spring Campelen Trawl Series	Gamma (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62	0.59 (0.23 – 1.35)
q.f.cam	Catchability, Canadian Fall Campelen Trawl Series	Gamma (μ=1, sd=1); 2.5% and 97.5% quantiles at 0.13 and 3.62	0.31 (0.12 – 0.72)
Sigma	Process error	Gamma (0.01,0.01)	0.14 (0.07 – 0.26)
tau.ynke	Observation error, Canadian Yankee Trawl	Gamma (0.01,0.01)	0.02 (0.001 – 0.29)
tau.eu	Observation error, European Union Series	Gamma (0.01,0.01)	0.61 (0.29 – 1.65)
tau.s.eng	Observation error, Canadian Spring Engel Trawl	Gamma (0.01,0.01)	0.01 (0.001 – 0.14)
tau.f.eng	Observation error, Canadian Fall Engel Trawl	Gamma (0.01,0.01)	0.36 (0.10 – 2.81)
tau.s.cam	Observation error, Canadian Spring Campelen Trawl	Gamma (0.01,0.01)	0.02 (0.001 – 0.11)
tau.f.cam	Observation error, Canadian Fall Campelen Trawl	Gamma (0.01,0.01)	0.22 (0.10 – 0.48)
MSY	Maximum Sustainable Yield	-	3.09 (0.24 – 8.26)
F_{MSY}	F at MSY	-	0.087 (0.007 – 0.25)
B_{MSY}	Biomass at MSY	-	33.5 (16.5 – 107.7)
DIC	Deviance Information Criteria	-	71

Table 4. ASPIC model format and parameter estimates for three non-equilibrium production model runs for Div. 3LNO Thorny Skate (refer to Prager 2014).

Model	3LNO Spring Campelen (1996-2013)	3LNO Spring Campelen (1996-2013)	3LNO Spring Campelen (1996-2013)
Tuning 1	3LNO Fall Campelen (1995-2013)	3LNO Spring Engel (1984-1995)	3LNO Spring Engel (1984-1995)
Tuning 2	.	.	3LNO Fall Campelen (1995-2013)
R^2 model	0.649	0.225	0.282
Tuning 1	0.528	0.314	0.286
Tuning 2	.	.	0.355
B1/K	3.64E-01	8.11E-02	9.75E-01
MSY	1.62E+04	1.13E+04	1.16E+04
K	8.46E+04	8.99E+04	8.85E+04
q(1) model	1.41E+00	1.63E+00	1.57E+00
q(2)	1.90E+00	9.63E-01	9.63E-01
q(3)	.	.	2.16E+00
B_{MSY}	4.23E+04	4.50E+04	4.43E+04
F_{MSY}	3.82E-01	2.52E-01	2.62E-01
B/B_{MSY}	1.84E+00	1.66E+00	1.70E+00
F/F_{MSY}	1.47E-01	2.34E-01	2.24E-01

Table 5. Empirical values for B_{MSY} and Limit Reference Points (LRPs), based on Canadian spring survey data for Div. 3LNO Thorny Skate in 1985-2014. LRP was calculated as 30% of B_{MSY} proxy.

Calculation Method for B_{MSY} proxy	**B_{MSY} proxy**	**LRP**
Geometric mean of full survey series (1985-2014)	98 167	29 450
Geometric mean of highest 2 successive years of full survey series (1985-86)	260 472	78 141
Highest survey biomass estimate, B_{max} (1985)	299 112	89 734
Geometric mean of highest 3 years of survey series (1985; 1986; 1988)	241 346	72 404

Table 6. Empirical values for B_{MSY} and Limit Reference Points, based on Canadian Campelen spring survey data for Div. 3LNO Thorny Skate in 1996-2014. LRP was calculated as 30% of B_{msy} proxy.

Calculation Method for B_{MSY} proxy	**B_{MSY} proxy**	**LRP**
Geometric mean of full Campelen series (1996-2014)	85 557	25 667
Geometric mean of highest 2 successive years of Campelen series (2013-14)	127 758	38 327
Highest survey biomass estimate, B_{max} (2013)	131 617	39 485
Geometric mean of highest 3 years of Campelen series (2007; 2013; 2014)	127 706	38 312

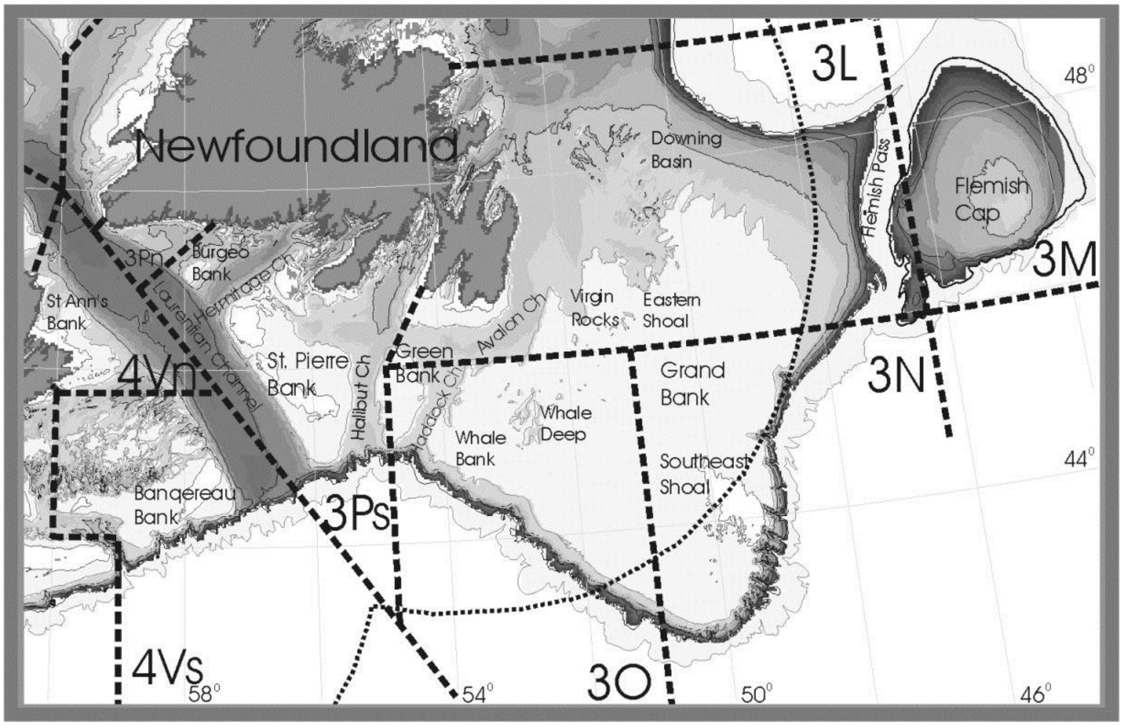


Figure 1. Map of the Grand Banks showing various banks, basins, and NAFO Divisions. Thick dotted lines delineate NAFO Divisions. The thin dotted curved line shows Canada's 200-mile limit: delineating Canadian territory from the NAFO Regulatory Area (NRA).

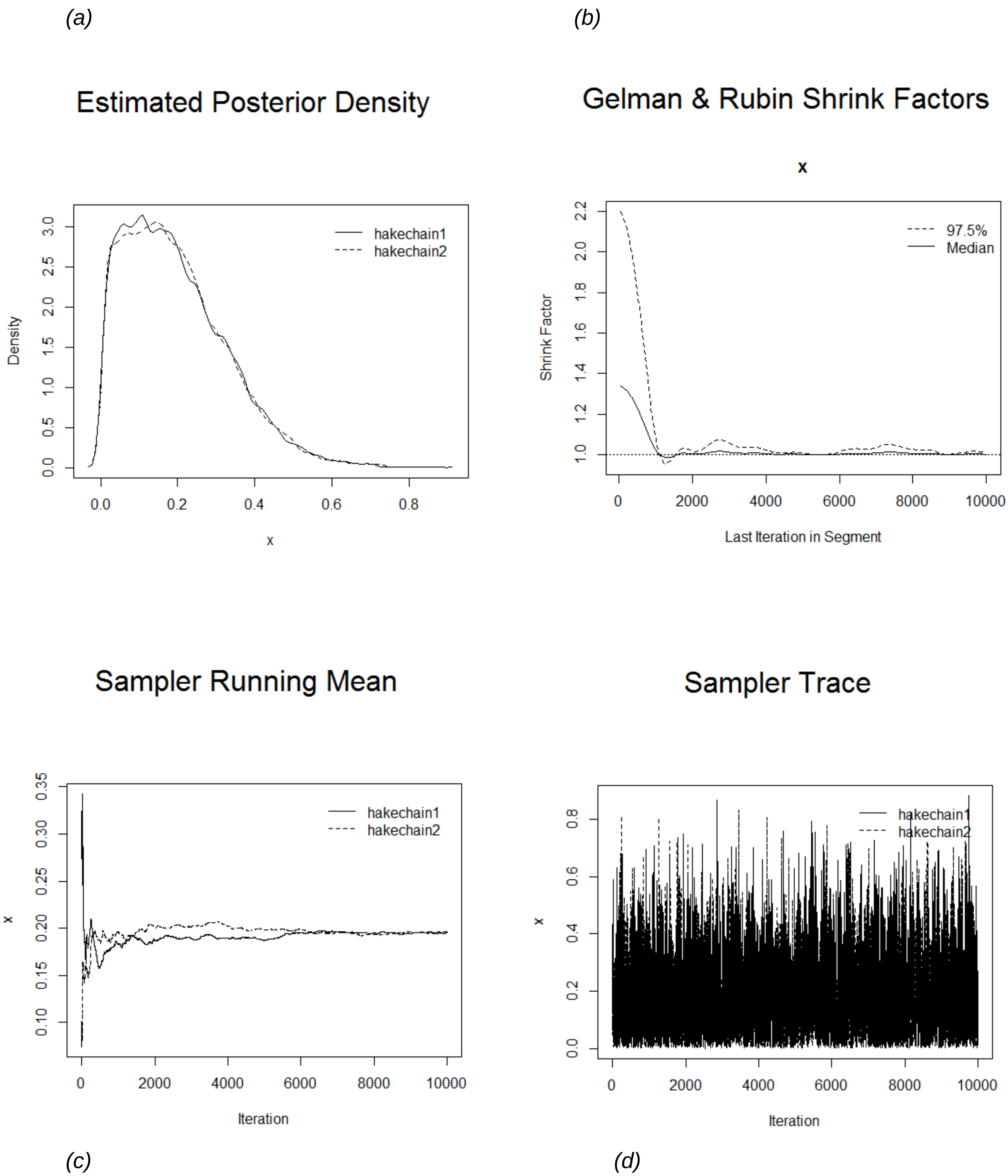


Figure 2. (a) Kernel density estimates of the posterior distribution of r for both chains. (b) Gelman and Rubin shrink factors for r. Gelman & Rubin shrink factors examining the reduction in bias in estimation. The shrink factor approaches 1 when the pooled within-chain variance dominates the between-chain variance. At that point, all chains have escaped the influence of their starting points. (c) Sampler running mean for r. (d) A time series trace of the sampled points for r in both chains.

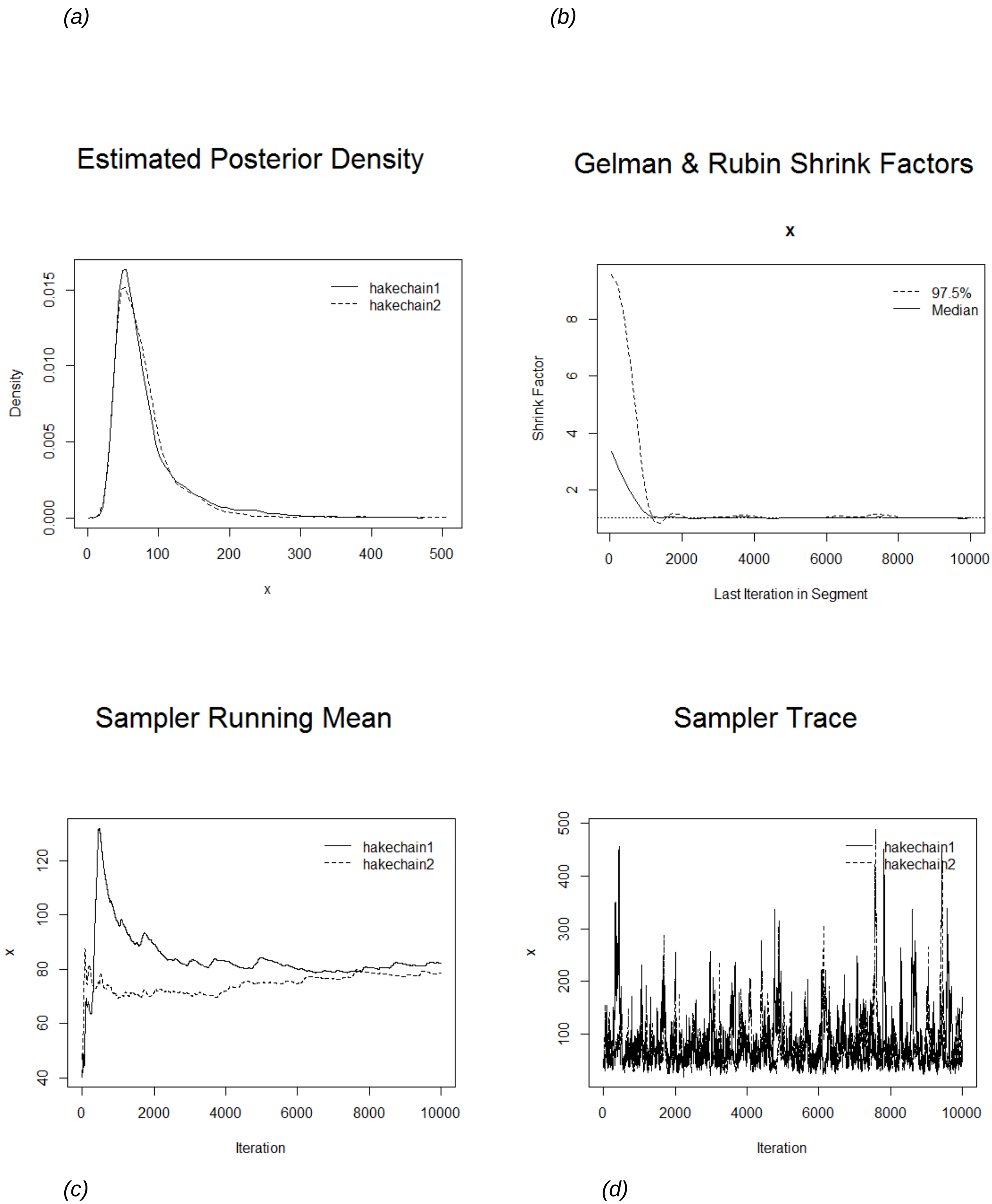


Figure 3. (a) Kernel density estimates of the posterior distribution of K for both chains. (b) Gelman and Rubin shrink factors for K. Gelman & Rubin shrink factors examining the reduction in bias in estimation. The shrink factor approaches 1 when the pooled within-chain variance dominates the between-chain variance. At that point, all chains have escaped the influence of their starting points. (c) Sampler running mean for K. (d) A time series trace of the sampled points for K in both chains.

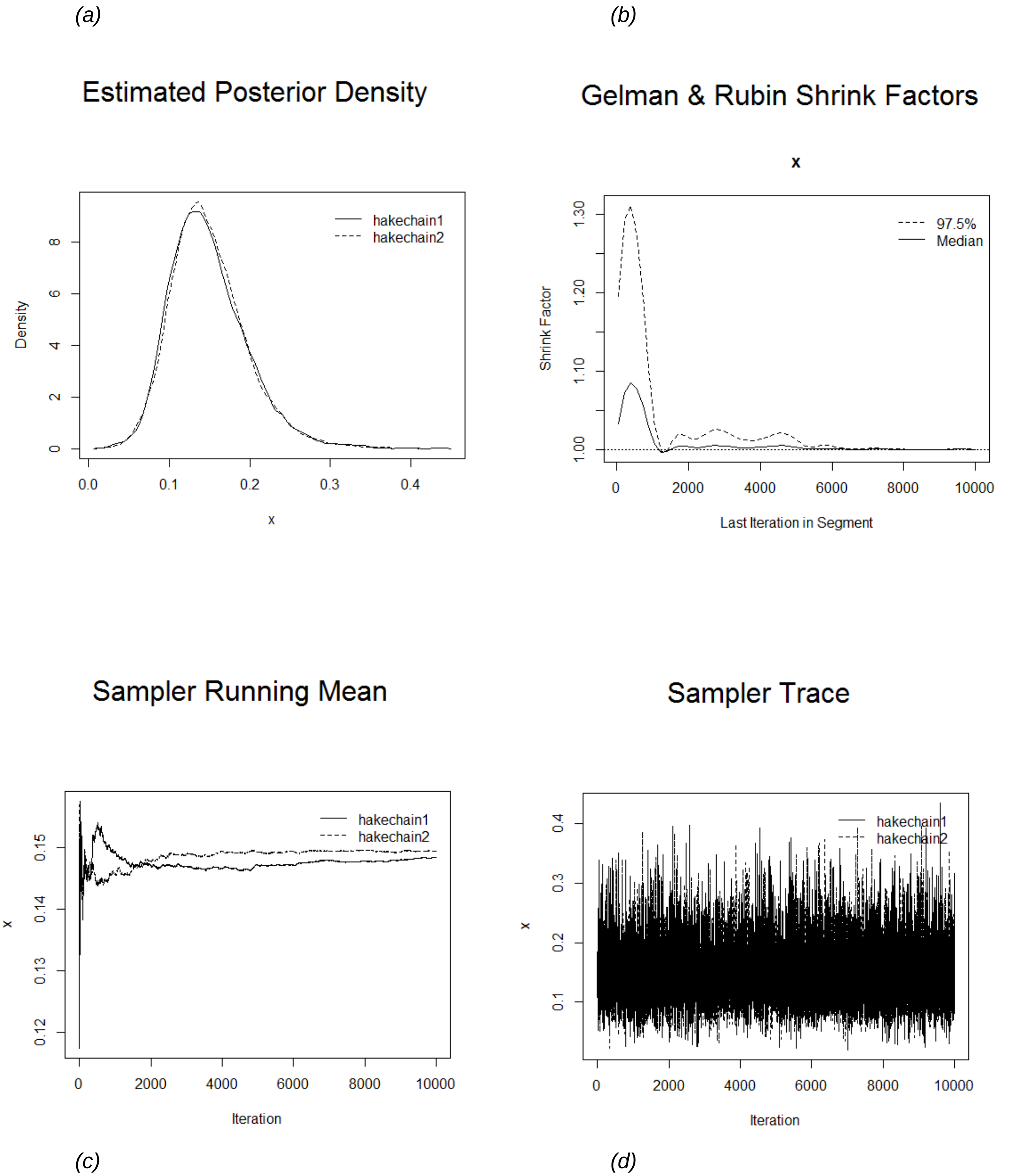


Figure 4. (a) Kernel density estimates of the posterior distribution of sigma (process error) for both chains. (b) Gelman and Rubin shrink factors for sigma. Gelman & Rubin shrink factors examining the reduction in bias in estimation. The shrink factor approaches 1 when the pooled within-chain variance dominates the between-chain variance. At that point, all chains have escaped the influence of their starting points. (c) Sampler running mean for sigma. (d) A time series trace of the sampled points for sigma in both chains.

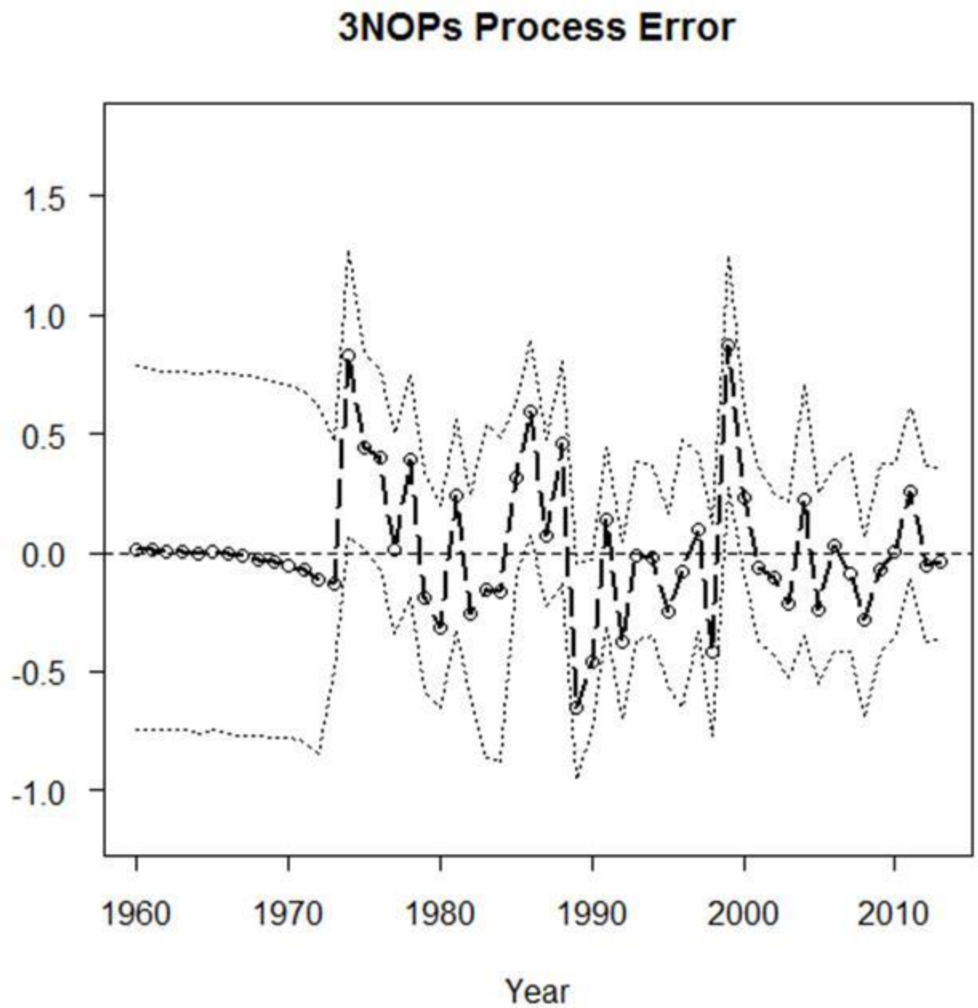


Figure 5. Process error (dotted lines represent the 95% credible interval) from the surplus production model for Div. 3NOPs White Hake, 1960-2013.

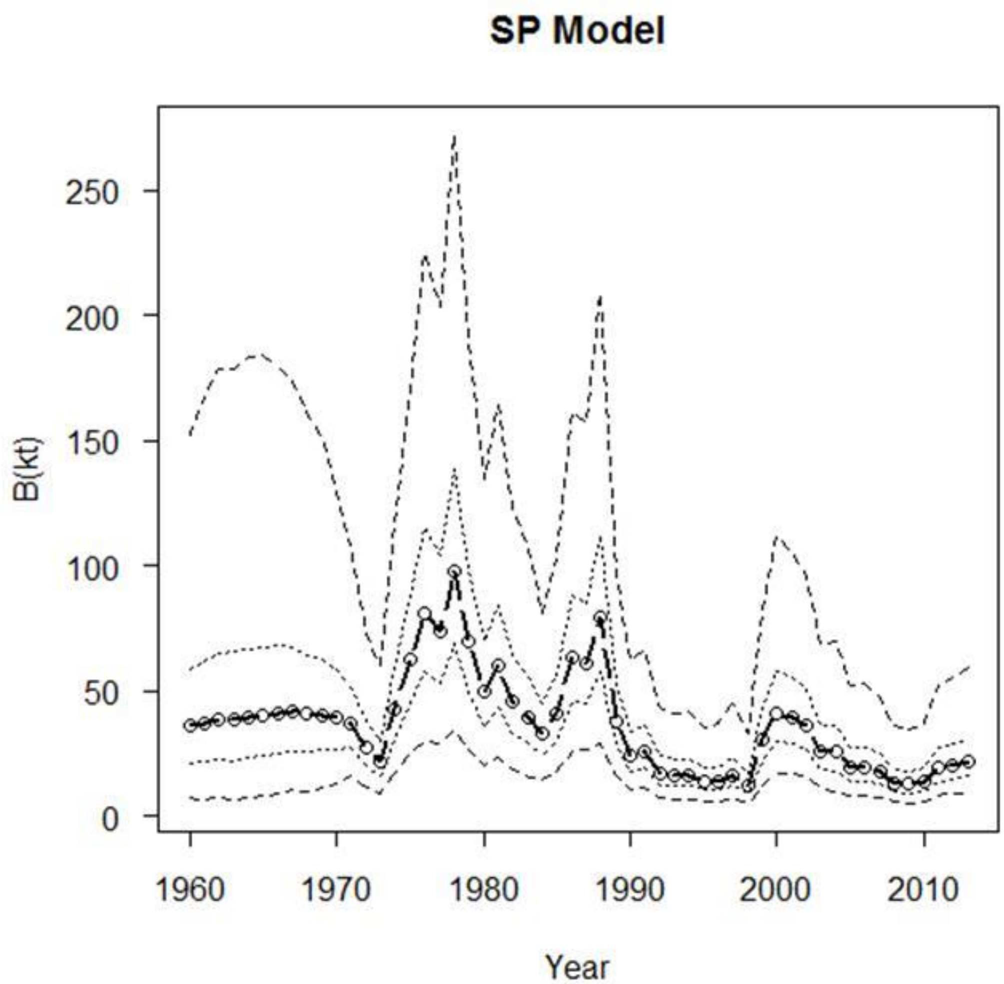


Figure 6. Schaefer surplus production model of median biomass (kt; bold dashed line) for Div. 3NOPs White Hake, 1960-2013. Dotted lines represent 50% and 95% credible intervals.

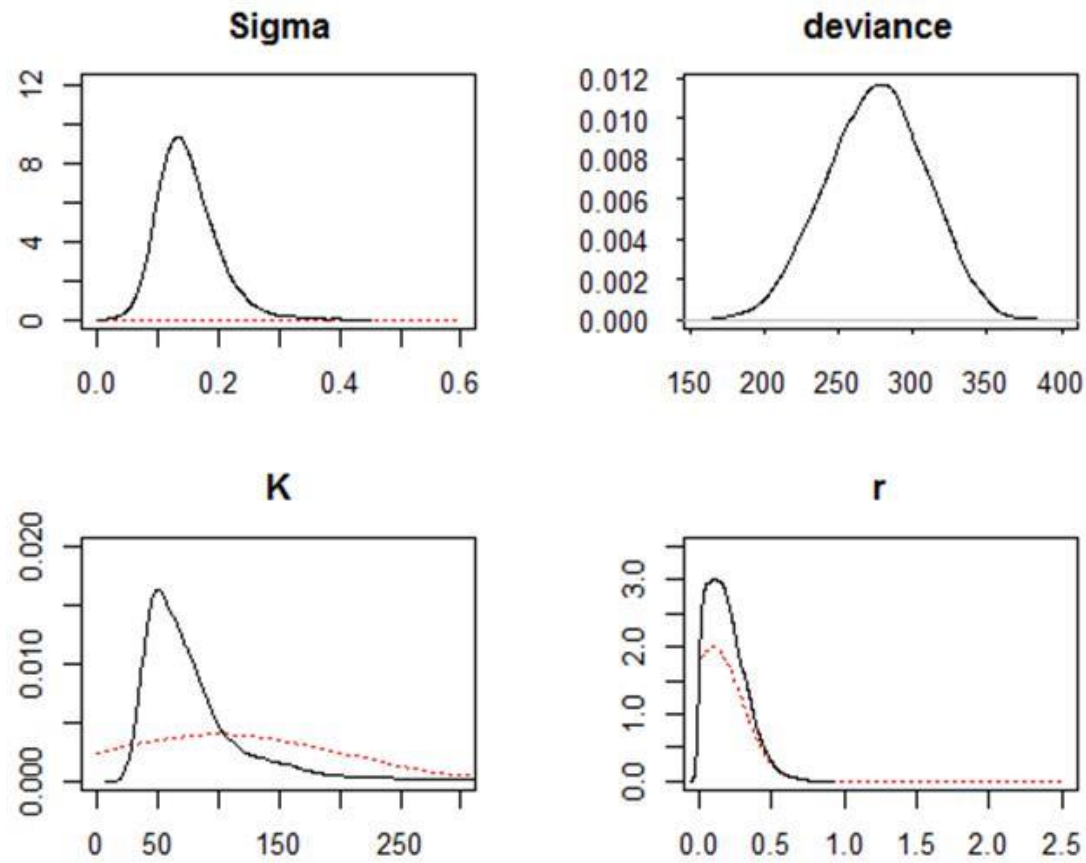


Figure 7. Posterior distributions for deviance, carrying capacity (K), intrinsic rate of population growth (r), and process error precision (Sigma) for Div. 3NOPs White Hake, 1960-2013. Prior distributions are shown for K, r, and Sigma (red dotted lines).

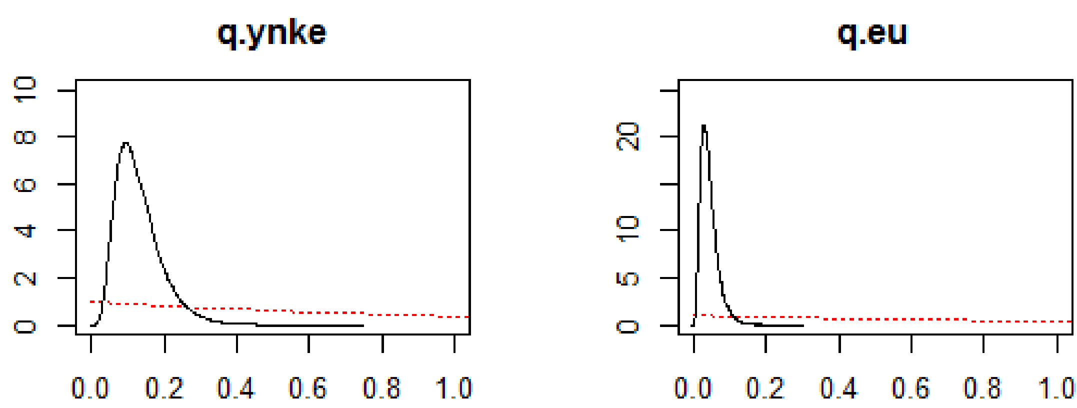


Figure 8. Posterior (solid line) and prior (red dotted lines) distributions of catchability (q) for the EU and Yankee time-series for Div. 3NOPs White Hake.

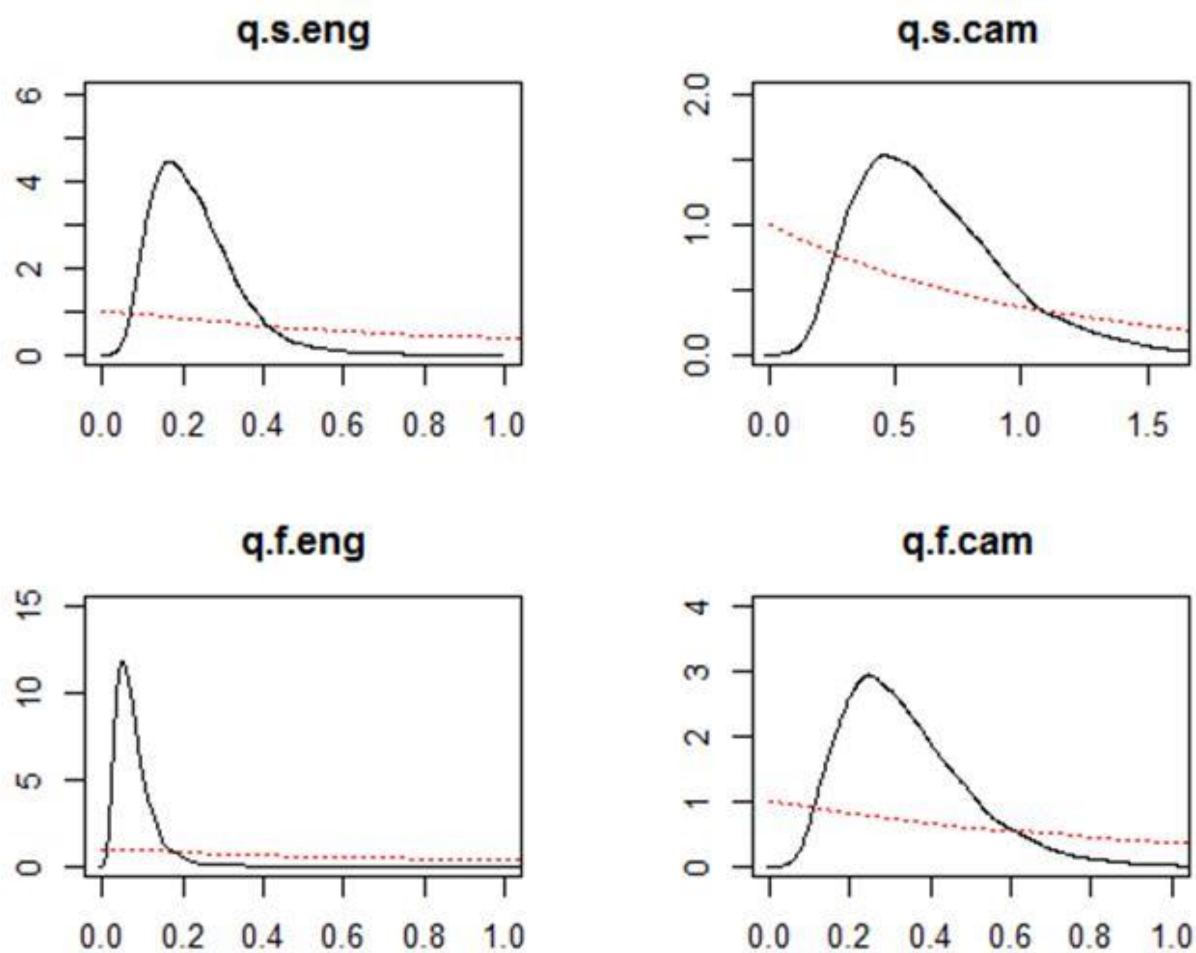


Figure 9. Posterior (solid line) and prior (red dotted lines) distributions of catchability (q) for the Engel and Campelen (spring and fall) time-series for Div. 3NOPs White Hake.

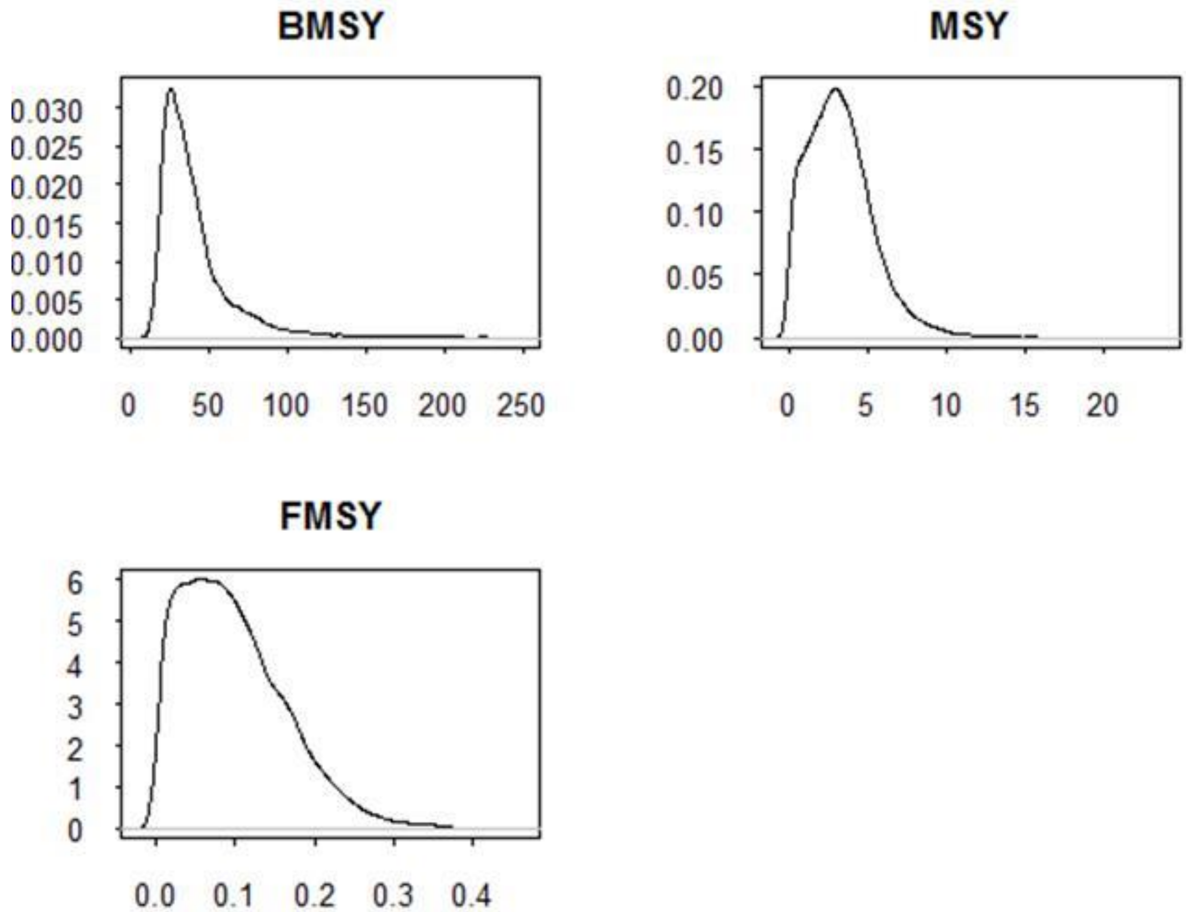


Figure 10. Posterior distributions for B_{MSY}, MSY, and F_{MSY} for Div. 3NOPs White Hake.

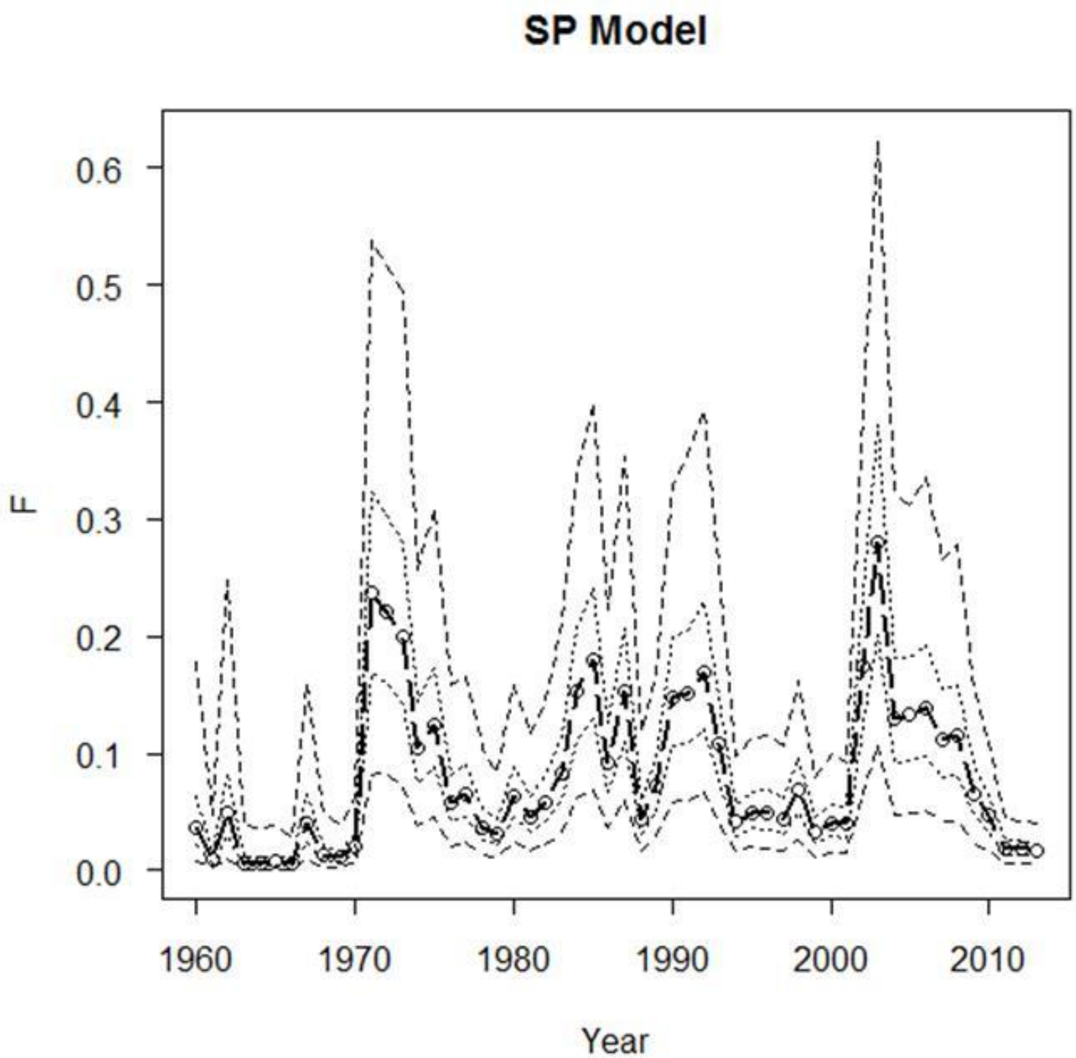
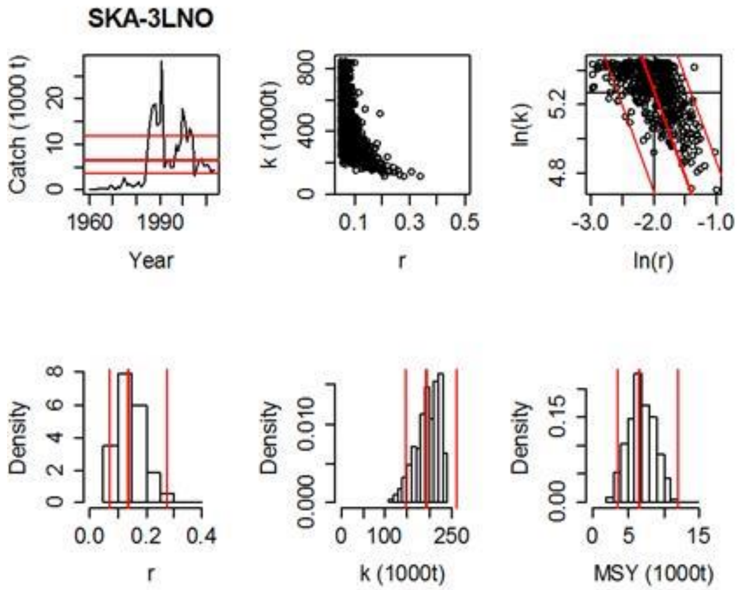


Figure 11. Median modeled values for fisheries mortality (F; bold dashed line) for Div. 3NOPs White Hake, 1960-2013. Dotted lines represent 50% and 95% credible intervals.

A)



B)

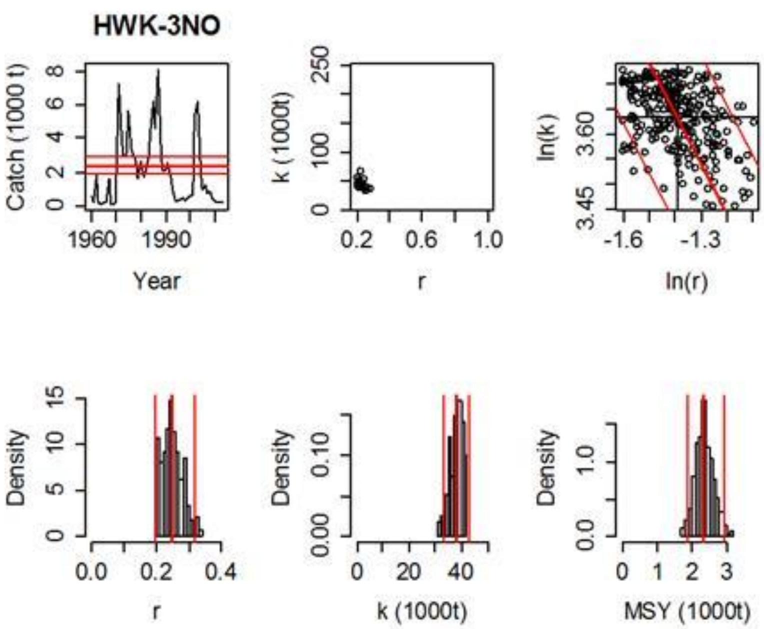
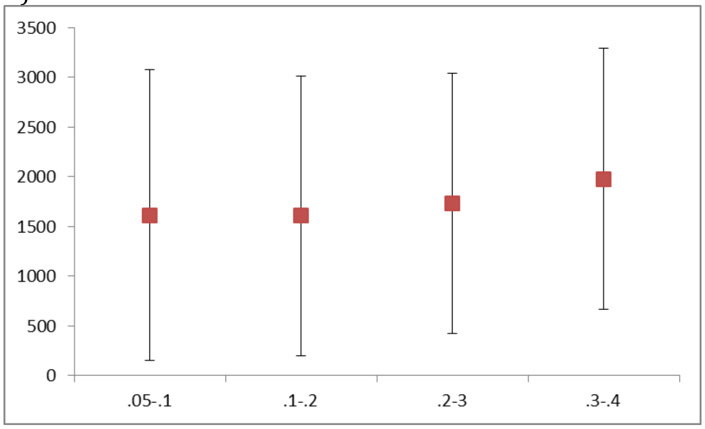
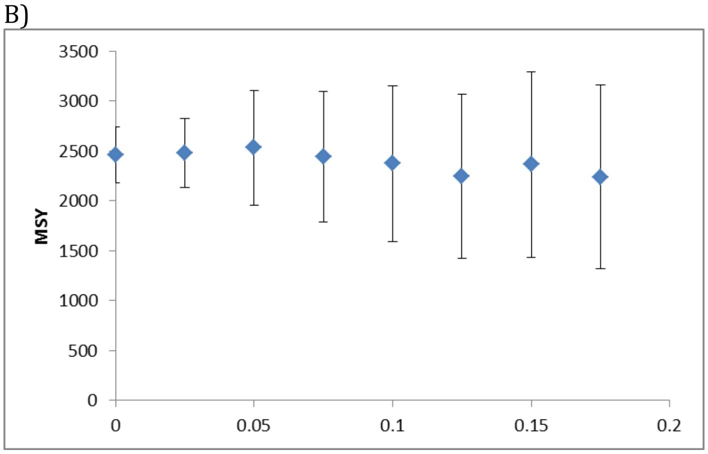


Figure 12. Catch-resilience model outputs for A) Div. 3LNO Thorny Skate, and B) Div. 3NO White Hake.

A)



B)



C)

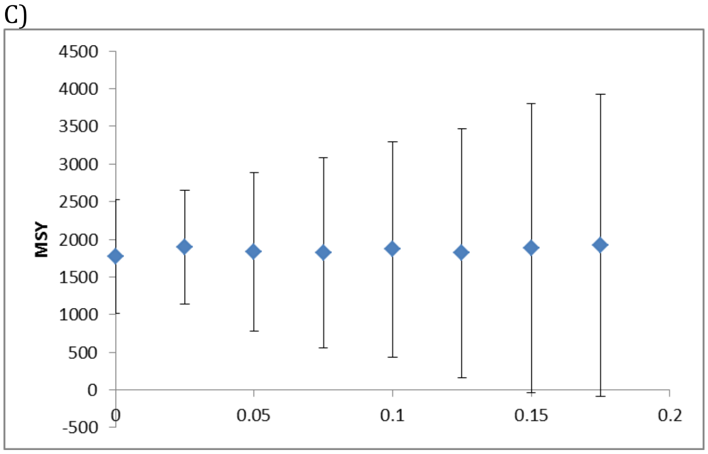


Figure 13. Impact of different A) levels of final biomass, B) process error at medium resilience, and C) process error at low resilience on MSY estimates from the White Hake catch-resilience model.

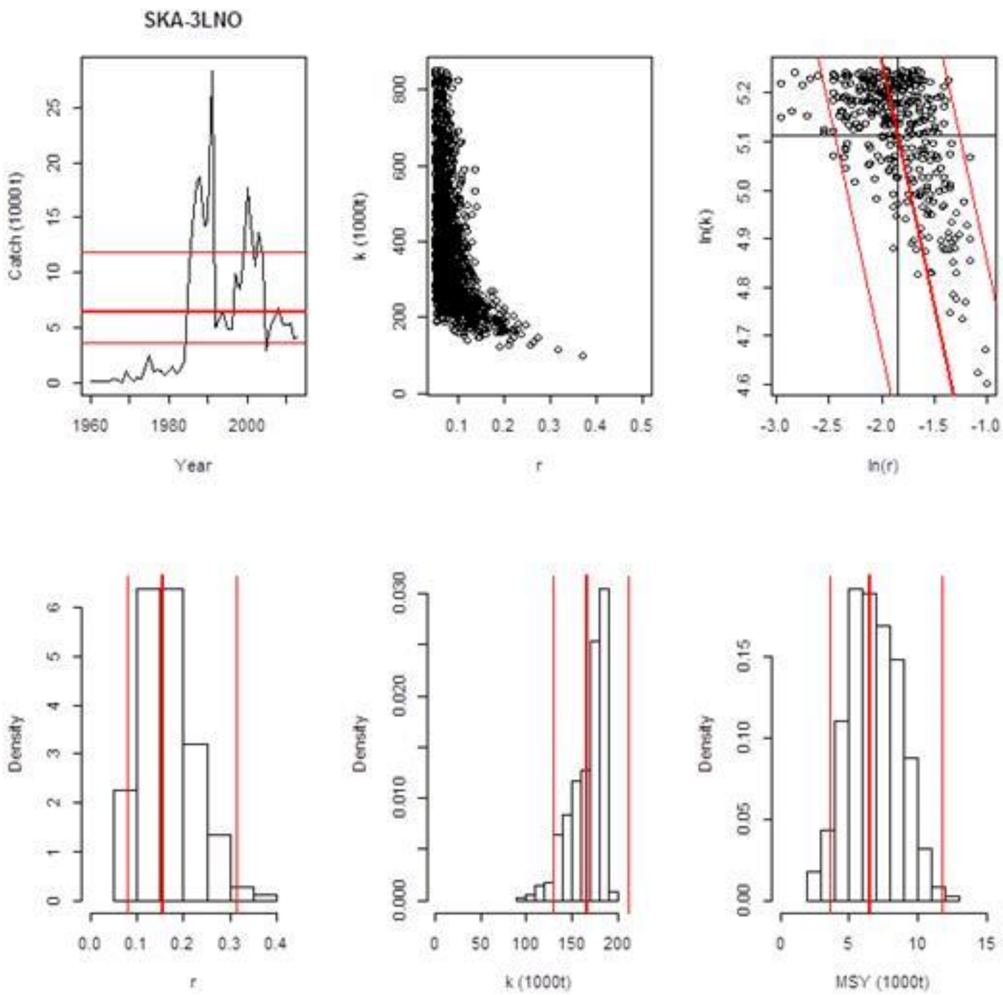


Figure 14. Final catch-resilience model output for Div. 3LNO Thorny Skate.

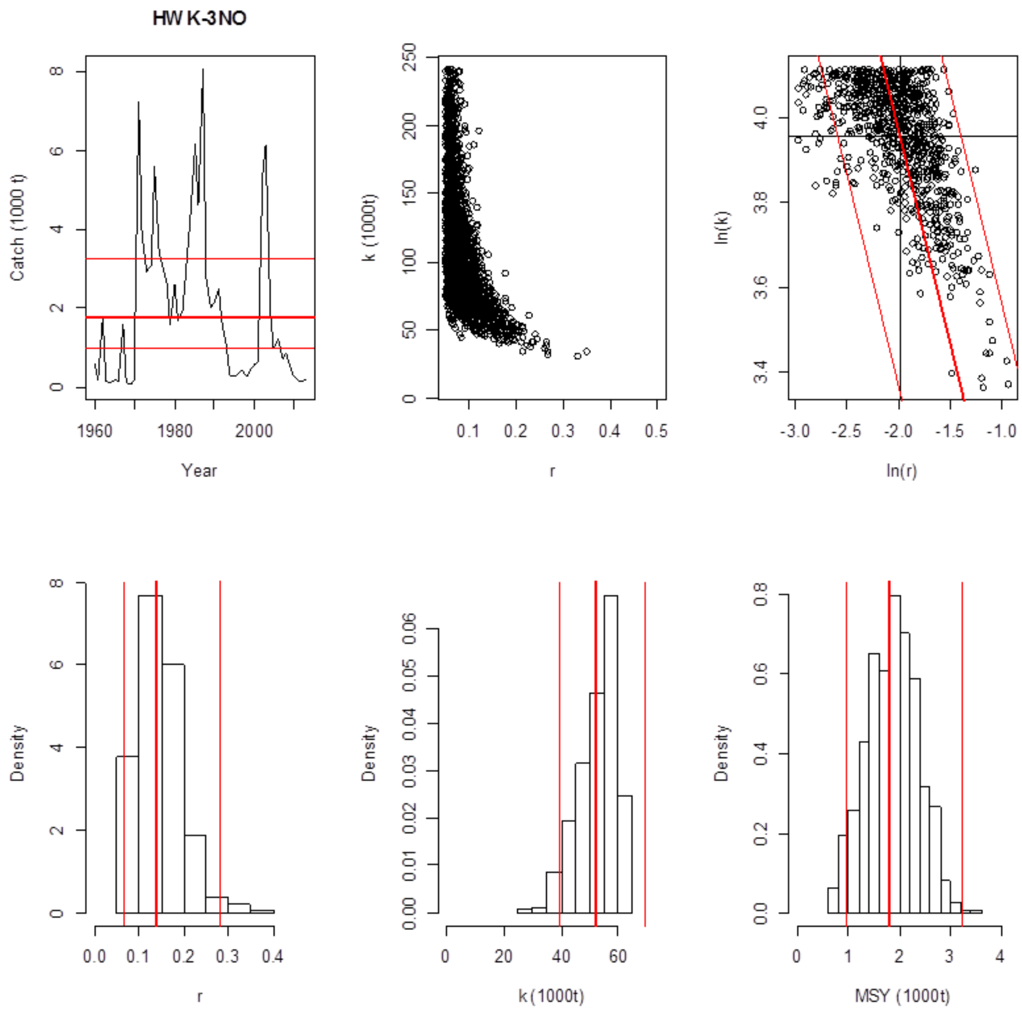


Figure 15. Final catch-resilience model output for Div. 3NO White Hake.

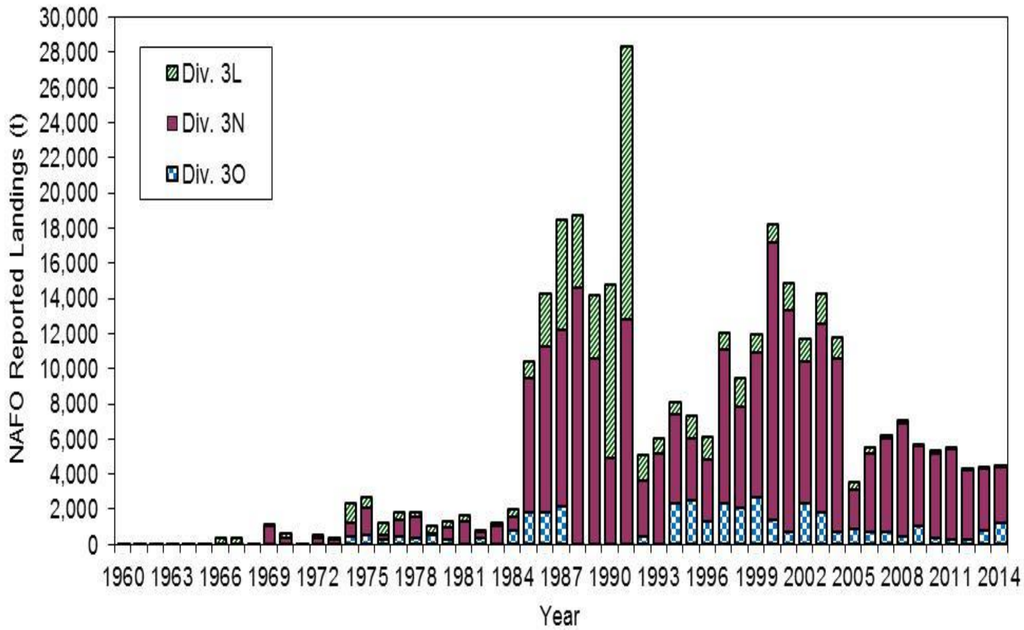
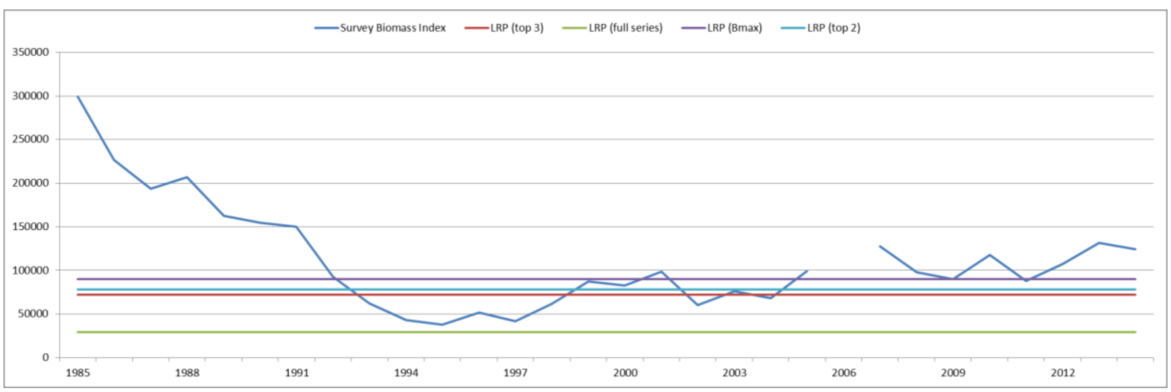


Figure 16. NAFO-reported landings (tons) of Div. 3LNO Thorny Skate by Canada and other countries, 1960-2014 (STATLANT-21A).



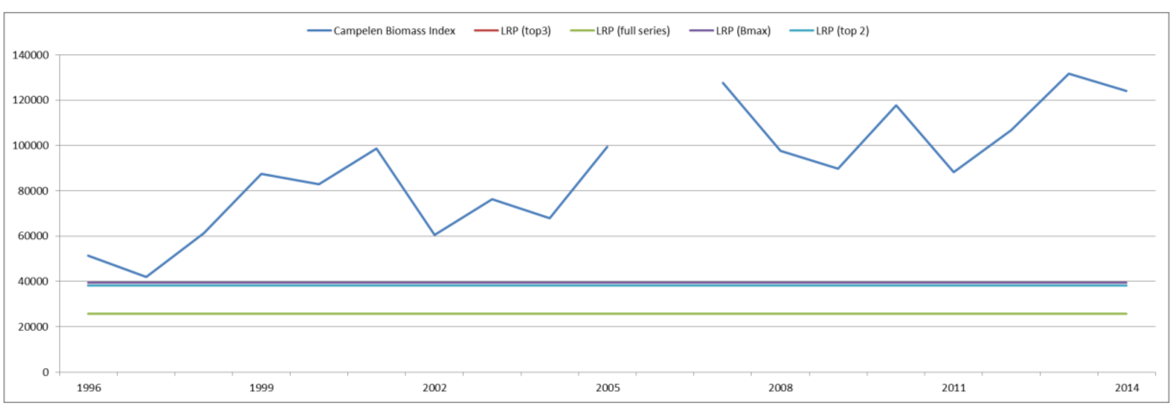


Figure 17. Empirical limit reference points for Div. 3LNO Thorny Skate based on various empirical proxies for B_{MSY}. Top panel represents full survey series, including Campelen equivalents, from 1985-2014. Bottom panel represents Campelen series only, from 1996-2014.

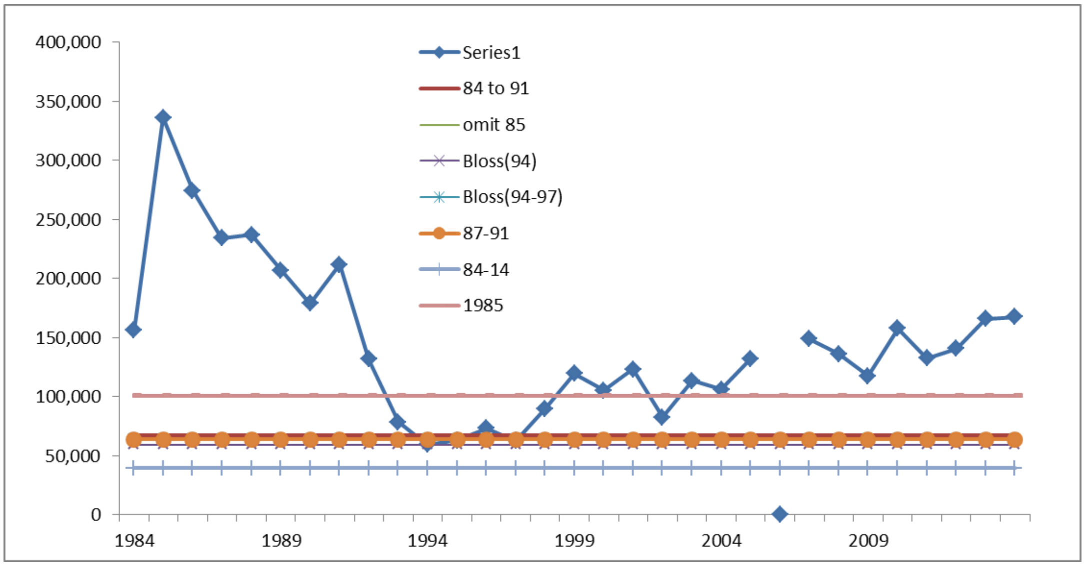


Figure 18. Empirical limit reference points for Div. 3LNOPs Thorny Skate based on various empirical proxies for B_{MSY}.

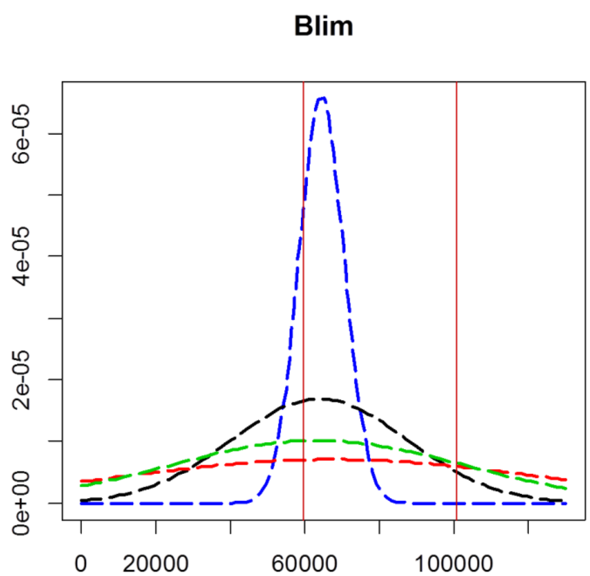


Figure 19. Empirical limit reference points for Div. 3LNOPs Thorny Skate based on various empirical proxies for B_{MSY} and B_{loss}

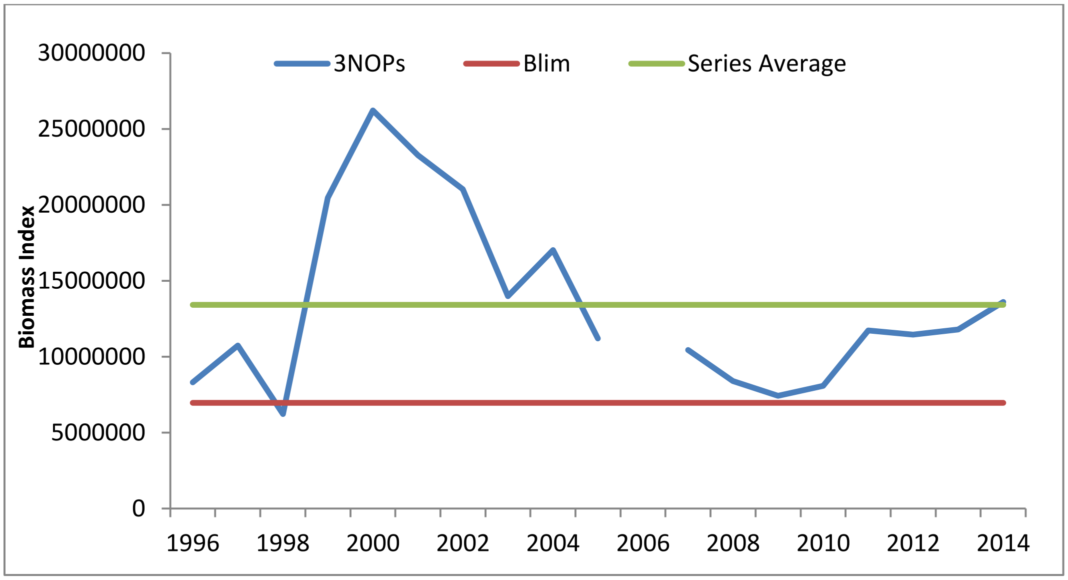


Figure 20. Empirical limit reference points for Div. 3NOPs White Hake based on 30% of the empirical proxies for B_{MSY} (average of 199-2001)