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Working Paper 2: Skates
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Methodology to determine overfished and overfishing reference points for skates

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Executive Summary

SPR-based reference points for three skate species, Barndoor, Winter, and Thorny, were derived from life-history parameters and fitted Beverton-Holt stock recruit relationships. Estimated overfishing reference points for these three species are $F_{25\%}$, $F_{37\%}$, and $F_{46\%}$, respectively. Future assessments could estimate comparable F's from mean length models (SEINE, e.g.), or from age-specific assessment models provided discards and landings could be disaggregated to species level. Estimates of overfished reference points are also SPR based, and are defined in terms of depletion, i.e. the proportion of spawners relative to unexploited levels. For Barndoor, Winter, and Thorny skates, the depletion reference points are 0.20, 0.27, and 0.32, respectively. Future assessments could determine stock status by comparing these depletion levels either with depletion in the surveys (provided information is available to estimate depletion for the first year in the survey) or from a stock assessment model that incorporates information about maturity. The same approach to derive reference points was attempted for Clearnose skate, however the parameter estimates from stock recruit curve were unrealistic. There are several important caveats for the methods used in this working paper, namely, that a fixed value of M was assumed for all ages, that the errors in variables problem was ignored in fitting the stock recruit relationship (*status quo*), and that no fishing is assumed to occur prior to the age of recruitment. The sensitivity to the assumed M value is addressed by exploring alternative values. If any fishing were to occur prior to the age of recruitment, then the estimated slope at the origin (*a* in the Beverton-Holt function) would be biased low, leading to an SPR reference point having a positive bias.

Introduction

Determination of stock status requires a set of reference points that are measured in the same units as estimates of current stock levels. The *de facto* target reference points are associated with Maximum Sustainable Yield (MSY), with limit reference points being some fraction of the target, typically one-half of the target. When MSY estimates can't be obtained, reference points based on spawning potential ratio (SPR) are a common proxy. There is abundant literature exploring the use of SPR (Goodyear 1977; Gabriel et al. 1989; Goodyear 1993; Mace 1993) and recommending appropriate levels of SPR (Clark 1991; Mace and Sissenwine 1993). Brooks et al. (*in prep.*) suggest that the appropriate level depends on species-specific characteristics, and that the level can be derived analytically from life-history parameters. The ability to express the reference point explicitly in terms of survival, maturity, and fecundity allows the proxy SPR level to be tailored to the species of interest. The appropriateness of the SPR level can be evaluated by inspection of the individual components to determine whether they are biologically realistic, and sensitivity to assumed rates can be calculated directly.

As is discussed in this WP, skate landings are not disaggregated to the species level, and there is uncertainty in the species identification of observed skate discards. The lack of species specific catch poses a major problem to conducting stock assessment analyses. The methods proposed in this working paper for deriving biological reference points use only data from the research surveys conducted by the Northeast Fisheries Science Center, thereby avoiding the potential problems associated with disaggregating the commercial catches.

Methods

Overfishing and overfished reference points are derived in terms of the SPR level that achieves maximum excess recruitment (MER, Goodyear 1980). MER differs from MSY in that it solves for the maximum yield in numbers rather than in weight. By comparison, $SPR_{MER} < SPR_{MSY}$ because the F that achieves MER is greater. This is due to the fact that MSY is achieved by allowing more fish to survive to older, hence heavier, ages. MER reference points are expressed in terms of maximum lifetime reproduction, $\hat{\alpha}$ (Myers et al., 1997, 1999), where

(1) $$\hat{\alpha} = a \sum_{age=r}^{A\max} p_{age} E_{age} \prod_{j=1}^{age-1} e^{-M_j} .$$

In (1), r is the age of recruitment, p_{age} is the proportion mature at age, E_{age} is the number of eggs produced at age, M is natural mortality, and a is the slope at the origin in the Beverton-Holt equation

(2) $$R = \frac{aS}{1 + S/K} .$$

The level of SPR corresponding to MER is given by

(3) $$SPR_{MER} = \frac{1}{\sqrt{\hat{\alpha}}}.$$

After calculating $\hat{\alpha}$, the resulting SPR_{MER} could be used to determine the overfishing target by calculating $F_{\%SPR}$. An overfished target could similarly be calculated from $\hat{\alpha}$ as

(4) $$\frac{SSB_{MER}}{SSB_0} = \frac{\sqrt{\hat{\alpha}} - 1}{\hat{\alpha} - 1}.$$

The calculated value in (4) gives a target depletion level, against which current estimates of spawner depletion could be compared.

In order to calculate the reference points, the components of $\hat{\alpha}$ are needed. First, the slope at the origin, *a*, was obtained by fitting Beverton-Holt curves to NEFSC fall bottom trawl survey data following Gedamke et al. (2009). Annual estimates of mean number of spawners per tow were derived by assuming knife-edged maturity at L_{50}. To obtain a time series of recruitment, the length corresponding to age of full vulnerability to the gear (L_{Crit}) was determined, and this was converted to a mean age from von Bertalanffy growth curves (Table 1). The stratified mean number of fish per tow above L_{50} (spawners) and for the year class corresponding to L_c (recruits) was then estimated for all years. The vector of mean number of spawners per year was then paired with the vector of mean number of recruits given the appropriate lag (Table 2). For instance, if recruitment was determined to occur at age 4, then a lag of 5 years was taken to account for the additional year spent as an egg. Years with missing data in these lagged pairs were dropped from the analysis. We emphasize that we used spawning number rather than spawning biomass. This is a more realistic approach for elasmobranchs, because they typically produce a few large eggs sacks (or pups, in the case of live bearers). Counting the number of spawners reflects the fact that there is a finite capacity for egg production and internal storage, whereas using spawning biomass as a proxy implies that fecundity increases by a power function with age. The fall survey was used because it is a longer time series and was more likely to reflect a wider range of observed stock sizes (NEFSC 2000).

Beverton-Holt curves were fit in ADMB (Otter Research, Ltd. 2004) assuming log-normal error in recruitment. We note that while the observations of spawners are not measured without error, the errors in variable problem is ignored (*status quo*).

The estimate of *a* obtained from the Beverton-Holt fits is a compound term that expresses survival from the egg stage (S_{egg}) to the age of recruitment (S_{r-1}) as well as the number of eggs produced per spawner (*E*), which is assumed to be a constant for all ages:

(5) $$a = ES_{egg} S_0 S_1 \cdots S_{r-1}.$$

Given the definition of $\hat{\alpha}$ in (1), the remaining term depends only on the natural mortality rate (*M*) assumed:

(6) $$\hat{\alpha} = a \sum_{age=r}^{A\max} p_{age} \prod_{j=1}^{age-r} e^{-M_j} = ae^{-(Amat-r)*M} \sum_{age=Amat}^{A\max} e^{-(age-Amat)*M} = a \frac{e^{-(Amat-r)*M}}{1-e^{-M}}.$$

The final term above is the closed form solution for the sum of a geometric series, which results for very large *Amax*, the maximum age. If Amax is 30 years or greater, then the difference between the finite sum and the infinite sum is small (Appendix 1). Estimates of an age-constant natural mortality (M) were calculated using four different methods based on life-history parameters: Pauly (1980), Hoenig (1983), and the Jensen (1996) age at maturity and k methods. Estimates ranged from 0.09 to 0.17 yr^{-1}, 0.15 to 0.18 yr^{-1}, and 0.17 to 0.25 yr^{-1} for winter, thorny and barndoor skates, respectively. The base case values used for these three species were 0.15, 0.18, and 0.18, respectively. For the clearnose skate, an M of 0.15 was used based on similarity with the other skates. Note that an estimate of water temperature is required for the Pauly (1980) estimator and we used 8.5 C as reported by Myers et al. (1997).

The reasonableness of the estimate of *a* can be evaluated by dividing *a* by *E*, the total number of eggs produced by a female in a year. The term remaining from this division is the cumulative survival from egg stage to the age of recruitment, $S_{egg}S_0S_1\ldots S_{r-1}$. Assuming that survival is constant at each of these pre-recruit stages, then the annual survival can be calculated as $(S_{egg}S_0S_1\ldots S_{r-1})^{1/r}$.

The sensitivity of $\hat{\alpha}$ and SPR based reference points was explored for a reasonable range of alternative M values that bracketed the estimates discussed above (0.10-0.25). The resulting SPR_{MER} and the level of F that would produce SPR_{MER} were calculated for each of the possible M values. Uncertainty in the reference points arising from uncertainty in *a* was evaluated with MCMC in AD Model Builder (Otter Research, Ltd, 2004). Two independent chains of length 1E+06 were simulated, with a thinning rate of 1/50. The first 35% of each chain was dropped (burn-in), and the remaining values were retained for analysis.

Results

The results of fitting Beverton-Holt relationships to the observed spawner and recruit data were evaluated by examination of diagnostic plots (Figures 1-4). For Barndoor, Thorny, and Winter skate, the diagnostics are acceptable, and the estimated parameters are reasonable (Table 3). However, for Clearnose skate, the residuals show unacceptable time trends (Figure 4) and the estimates are not reasonable (Tables 3 and 4; steepness of about 0.96).

The estimated precision for the reference points only reflects the precision of the estimated stock-recruit parameters (*a* and *K*). Sensitivity of the estimated reference points and the associated fishing mortality rate for alternative values of M are given in Tables 5-7. For higher M, SPR_{MER} and depletion at MER are also higher, which equates to a lower F. This may initially seem counterintuitive, for one often finds that assuming a higher M leads to a higher estimate of F_{MSY} in a typical stock assessment. However, in this case, the result of a higher M producing a lower $F_{\%SPR}$ is due to the direct impact of M on the unexploited calculation of spawners per recruit (Table 8). It is this parameter that scales *a* to yield $\hat{\alpha}$, from which the reference points are estimated.

Barndoor skate

There were 14 observations of (S_y, R_y) for Barndoor skate from the fall NEFSC bottom trawl survey (Table 2). The estimated slope at the origin was 5.78, which gives a maximum lifetime reproduction of 15.61 ($\hat{\alpha}$, Table 3). From equations (3) and (4) above, SPR_{MER}=0.25 and the depletion of spawners at MER (S_{MER}/S_0) is 0.20. The estimated fishing mortality that achieves an SPR of 0.25 is $F_{25\%}$= 0.18. The implied annual survival during the pre-recruit stage is 0.27/year for three years (egg stage to age 2, Table 3). The long right tail in the posterior distribution of the slope at the origin (*a*) reflects the poorer precision of that parameter (CV=50%). By comparison, the reference points were twice as precise.

Winter skate

There were 36 observations of (S_y, R_y) for Winter skate from the fall NEFSC bottom trawl survey (Table 2). The estimated slope at the origin was 2.94, which gives a maximum lifetime reproduction of 7.39 ($\hat{\alpha}$, Table 3). From equations (3) and (4) above, SPR_{MER}=0.37 and the depletion of spawners at MER (S_{MER}/S_0) is 0.27. The estimated fishing mortality that achieves an SPR of 0.37 is $F_{37\%}$=0.08. The implied annual survival during the pre-recruit stage is 0.43/year for five years (egg stage to age 4, Table 3). As was the case with barndoor skate, the estimated CV for the slope at the origin (*a*) was twice that of the reference points (0.39 for *a* versus 0.19 and 0.14 for SPR_{MER} and depletion at MER).

Thorny skate

There were 40 observations of (S_y, R_y) for Thorny skate from the fall NEFSC bottom trawl survey (Table 2). The estimated slope at the origin was 2.71, which gives a maximum lifetime reproduction of 4.67 ($\hat{\alpha}$, Table 3). From equations (3) and (4) above, SPR_{MER}=0.46 and the depletion of spawners at MER (S_{MER}/S_0) is 0.32. The estimated fishing mortality that achieves an SPR of 0.46 is $F_{46\%}$=0.07. The implied annual survival during the pre-recruit stage is 0.44/year for five years (egg stage to age 4, Table 3). As was the case with barndoor skate, the estimated CV for the slope at the origin (*a*) was twice that of the reference points (0.31 for *a* versus 0.16 and 0.11 for SPR_{MER} and depletion at MER).

Clearnose skate

There were 28 observations of (S_y, R_y) for Clearnose skate from the fall NEFSC bottom trawl survey (Table 2). The estimated slope at the origin was 101.10, which gives a maximum lifetime reproduction of 15.61 ($\hat{\alpha}$, Table 3). The diagnostics were not acceptable, and the parameter estimates were unrealistic (steepness=0.96, Table 4); therefore, the estimated reference points are considered inappropriate for management advice. No MCMC simulations were conducted for this species based on the poor initial model fit.

Conclusions

Assessment of skate species has proven to be difficult, due to the aggregated nature of commercial landings and the lack of data on discards for much of the time series. The difficulty applies equally to the estimation of reference points for skates. The methodology of Gedamke et al. (2008) provided a method to estimate the slope at the origin for Beverton-Holt stock recruit relationships. Management reference points are strongly dependent on the stock recruitment curve, and the slope parameter is a key component in determining appropriate reference points. Combining the slope with other biological parameters, the analytic solutions for SPR_{MER} were derived from results in Brooks et al. (2008, *in preparation*).

Data were sufficient to attempt fitting stock recruit curves to four skate species: Barndoor (14 data points), Thorny (40 data points), Winter (36 data points), and Clearnose skate (28 data points). The diagnostics were acceptable for all but Clearnose skate, and the parameter estimates for the remaining three species appear reasonable. The resulting reference point estimates are on a scale that would be compatible with existing assessment methodology. For example, models such as SEINE (2008; NMFS Toolbox module based on Gedamke and Hoenig, 2006) , or other mean length based models, could provide estimates of fishing mortality, provided the lengths examined included only those above the full vulnerability to the gear. These assessment-based estimates of F could then be compared to the $F_{\%SPR}$ estimated in this working paper to determine the overfishing status. The overfished status could be determined by examining the implied depletion of spawners, for example by examining the final point in the scaled index of mean spawners/tow ($S_y/S_{y=1}$). The scaled index of spawners would be depletion from an unexploited state if it was appropriate to assume that the stock was unexploited in year $y=1$. If that is not the case, then the index could be multiplied by a scalar, d, which reflects a measure (or expert opinion) of the level of depletion in year $y=1$. Alternatively, if algorithms to dissociate the landings and to hindcast discards are developed and agreed upon, then traditional stock assessment methods could be applied to estimate current levels of fishing mortality and stock size.

These SPR reference points were bounded by considering sensitivity across a reasonable range of natural mortality (M) levels.

Beverton-Holt curves were fit, but no Ricker curves were attempted because there is no obvious mechanism that would lead to overcompensation, nor is there data available that would suggest it.

As is common in most stock-recruit curve fitting exercises, the error in observed spawners per tow is ignored. Walters and Ludwig (1981) suggest that the estimation performance from ignoring error in the ‘independent’ variable is worse if the observations all come from a period where the stock was already heavily exploited. As the time series used in fitting Beverton-Holt curves extends back to the 1960s, it may be that a fairly broad range of spawning stock sizes is reflected in the observations.

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Appendix 1. Evaluation of the bias generated by calculating unexploited spawners per recruit, spr(F=0), as either an infinite sum or by calculating the series only up to the maximum age (Amax). For this exercise, the ratio between terms in the series is $r=e^{-M}$. The infinite sum is $1/(1-r)$ while the sum to Amax is given by $(1-r^{Amax+1})/(1-r)$. The combinations of Alag and M in this illustration correspond to the observed pairs for skate species examined in this document.

Amax	Alag	M	spr(F=0) Sum to Amax	spr(F=0) Infinite sum	% bias (Infinite sum - Sum to Amax)/ Sum to Amax
15	4.5	0.18	2.36	2.70	14%
20	4.5	0.18	2.56	2.70	5%
25	4.5	0.18	2.64	2.70	2%
30	4.5	0.18	2.68	2.70	1%
35	4.5	0.18	2.69	2.70	0%
40	4.5	0.18	2.70	2.70	0%
15	7	0.15	1.86	2.51	35%
20	7	0.15	2.20	2.51	14%
25	7	0.15	2.37	2.51	6%
30	7	0.15	2.44	2.51	3%
35	7	0.15	2.48	2.51	1%
40	7	0.15	2.50	2.51	1%
15	7	0.18	1.38	1.72	25%
20	7	0.18	1.58	1.72	9%
25	7	0.18	1.67	1.72	3%
30	7	0.18	1.70	1.72	1%
35	7	0.18	1.71	1.72	1%
40	7	0.18	1.72	1.72	0%

Table 1. Criteria used to define the age at recruitment (full vulnerability to the survey gear), the age at maturity (assumed to be knife-edged), and the NEFSC bottom trawl survey used to generate paired observations of spawners and recruits.

Parameter	Barndoor	Thorny	Winter	Clearnose
Length range at full vulnerability	55-69 cm	46-54 cm	40-44 cm	42-50 cm
Age at full vulnerability (recruitment)	2	4	4	4
Length at full maturity	116	88	76	66
Age at full maturity	6.5	11	11	6
NEFSC survey used (SPRING/FALL)	FALL	FALL	FALL	FALL

Table 2. Pairs of observed number of spawners/tow and number of recruits/tow for Barndoor, Thorny, Winter, and Clearnose skate. The year indicates the year that eggs were spawned. Note that the year differs between the skate species.

	Barndoor			Thorny			Winter			Clearnose	
Year	**Spawners**	**Recruits**	**Year**	**Spawners**	**Recruits**	**Year**	**Spawners**	**Recruits**	**Year**	**Spawners**	**Recruits**
1963	0.0592	0.1703	1963	0.5141	0.1175	1967	0.1024	0.3502	1975	0.0022	0.0692
1964	0.0194	0.0181	1964	0.3766	0.1723	1968	0.0657	0.2330	1976	0.0106	0.0489
1965	0.0092	0.0572	1965	0.3774	0.2832	1969	0.0448	0.1035	1977	0.0459	0.0350
1967	0.0055	0.0072	1966	0.6772	0.1568	1970	0.1228	0.0197	1978	0.0044	0.0026
1968	0.0047	0.0495	1967	0.1945	0.1997	1971	0.0358	0.0256	1979	0.0414	0.0306
1993	0.0100	0.0039	1968	0.3602	0.2635	1972	0.1025	0.1320	1980	0.0902	0.0516
1997	0.0040	0.0073	1969	0.4592	0.1408	1973	0.2083	0.0442	1981	0.0094	0.0621
1998	0.0053	0.0286	1970	0.6659	0.0716	1974	0.0895	0.1283	1982	0.0216	0.0689
1999	0.0106	0.0747	1971	0.5239	0.0853	1975	0.0688	0.1684	1983	0.0031	0.0627
2000	0.0039	0.0388	1972	0.3609	0.1978	1976	0.2673	0.1504	1984	0.0214	0.0573
2001	0.0219	0.0295	1973	0.4130	0.4055	1977	0.3921	0.2500	1985	0.0395	0.0957
2002	0.0297	0.0890	1974	0.1989	0.1295	1978	0.5990	0.1135	1986	0.0162	0.2069
2003	0.0151	0.0691	1975	0.1850	0.1982	1979	0.6634	0.3065	1987	0.0456	0.0528
2004	0.0642	0.1059	1976	0.1344	0.2253	1980	0.6649	0.2047	1988	0.0413	0.0969
			1977	0.2131	0.0258	1981	0.5778	0.1448	1989	0.0161	0.1828
			1978	0.2172	0.1476	1982	0.7272	0.4153	1990	0.0374	0.0408
			1979	0.2480	0.1543	1983	1.4457	0.3024	1991	0.1917	0.0732
			1980	0.2864	0.1213	1984	1.2900	0.1518	1992	0.0455	0.0653
			1981	0.1973	0.0380	1985	1.4719	0.2345	1993	0.0642	0.3494
			1982	0.0384	0.1114	1986	2.1119	0.3594	1994	0.1021	0.1941
			1983	0.1424	0.0934	1987	1.3070	0.2254	1995	0.0555	0.1712
			1984	0.1925	0.1368	1988	0.9280	0.2203	1996	0.0452	0.2421
			1985	0.1490	0.1241	1989	0.6537	0.3772	1997	0.1473	0.2520
			1986	0.1069	0.1899	1990	1.0601	0.3256	1998	0.1215	0.1001
			1987	0.0321	0.0723	1991	0.6036	0.2136	1999	0.2430	0.0612
			1988	0.0812	0.1316	1992	0.3846	0.1167	2000	0.2059	0.0582
			1989	0.0997	0.2209	1993	0.1721	0.1284	2001	0.2110	0.1417
			1990	0.1313	0.1271	1994	0.1436	0.2063	2002	0.1428	0.1216
			1991	0.1087	0.0782	1995	0.1048	0.2237			
			1992	0.0449	0.0605	1996	0.1557	0.2399			
			1993	0.0963	0.0370	1997	0.1460	0.1339			
			1994	0.0655	0.0481	1998	0.3493	0.0740			
			1995	0.0270	0.0605	1999	0.2881	0.2109			
			1996	0.0450	0.0568	2000	0.4001	0.2149			
			1997	0.0528	0.0214	2001	0.3131	0.2157			
			1998	0.0516	0.1567	2002	0.6870	0.2470			
			1999	0.0197	0.0482						
			2000	0.0605	0.0175						
			2001	0.0127	0.0311						
			2002	0.0303	0.0234						

Table 3. Estimates of Beverton-Holt parameters, and implied annual survival $(S_{egg}S_0 \ldots S_{r-1})^{1/r}$ for the product of total number of eggs per female per year and cumulative survival to recruitment, $S_{egg}S_0 \ldots S_{r-1}$.

Parameter	Barndoor	Thorny	Winter	Clearnose
a (slope at origin)	5.78 (0.50)	2.71 (0.31)	2.94 (0.39)	*19.01 (0.65)*
K	0.01 (1.65)	0.08 (0.48)	0.10 (0.52)	*0.01 (0.80)*
E (Total Number of eggs/female)	80	41	48	40
$S_{egg}S_0 \ldots S_{r-1}$	0.07	0.03	0.04	*0.24*
$(S_{egg}S_0 \ldots S_{r-1})^{1/r}$	0.27	0.51	0.50	0.83

Table 4. Species specific reference points (and CV) for the assumed natural mortality rate (M), the estimated maximum lifetime reproduction ($\hat{\alpha}$), and the implied steepness (steepness is related to $\hat{\alpha}$ as $\hat{\alpha}/(\hat{\alpha}+4)$). No reference points are given for Clearnose skate as diagnostics and estimates were unsatisfactory.

Parameter	Barndoor	Thorny	Winter	Clearnose
M (natural mortality)	0.18	0.18	0.15	*0.15*
$\hat{\alpha}$	15.61 (0.50)	4.67 (0.31)	7.39 (0.39)	101.10 (0.33)
steepness	0.80	0.54	0.65	0.96
SPR_{MER}	0.25 (0.25)	0.46 (0.16)	0.37 (0.19)	N/A
S_{MER}/S_0	0.20 (0.20)	0.32 (0.11)	0.27 (0.14)	N/A

Table 5. Sensitivity of SPR_{MER} reference points to the assumed level of natural mortality (M). For each species, the value in bold is the base case value assumed for M.

M value	Barndoor	Thorny	Winter
0.10	0.16	0.27	0.26
0.15	0.22	0.38	**0.37**
0.18	**0.25**	**0.46**	0.44
0.20	0.28	0.52	0.50
0.25	0.34	0.68	0.66

Table 6. Sensitivity of depletion reference points (S_{MER}/S_0)to the assumed level of natural mortality (M). For each species, the value in bold is the base case value assumed for M.

M value	Barndoor	Thorny	Winter
0.10	0.14	0.21	0.20
0.15	0.18	0.28	**0.27**
0.18	**0.20**	**0.32**	0.31
0.20	0.22	0.34	0.33
0.25	0.26	0.41	0.40

Table 7. Estimated fishing mortality rate (F) that achieves SPR_{MER} given the base value assumed for M. For each species, the value in bold is the base case value assumed for M.

M value	Barndoor	Thorny	Winter
0.10	0.19	0.10	0.10
0.15	0.18	0.08	**0.08**
0.18	**0.18**	**0.07**	0.07
0.20	0.17	0.06	0.06
0.25	0.15	0.04	0.04

Table 8. Effect of Alag (difference in years between maturity and recruitment ages) and M on the unexploited spawners per recruit, spr(F=0).

Alag	M	spr(F=0)
4.5	0.10	6.70
4.5	0.12	5.15
4.5	0.15	3.66
4.5	0.18	2.70
4.5	0.20	2.24
4.5	0.22	1.88
7	0.10	5.22
7	0.12	3.82
7	0.15	2.51
7	0.18	1.72
7	0.20	1.36
7	0.22	1.09

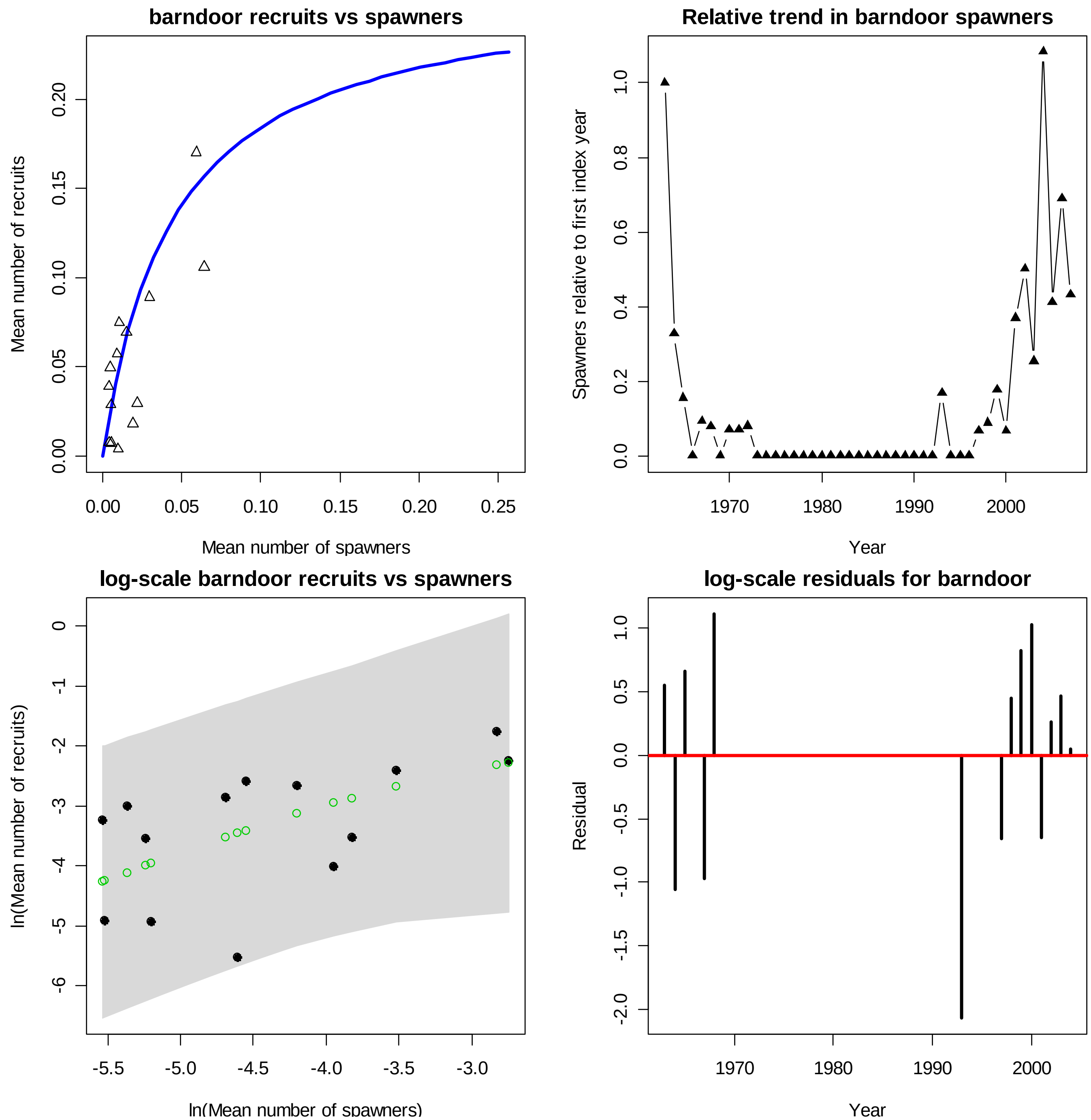

Figure 1. Diagnostic plots for **barndoor** skate: observed (open triangles) versus predicted mean number of recruits (top left), observed time series of spawners scaled by the first observation ($S_y/S_{y=1}$) (top right), log-scale fit of observed (solid circles) to predicted (open circles) number of recruits/tow with shaded 95% confidence interval (bottom left), and standardized log-scale residuals (bottom right).

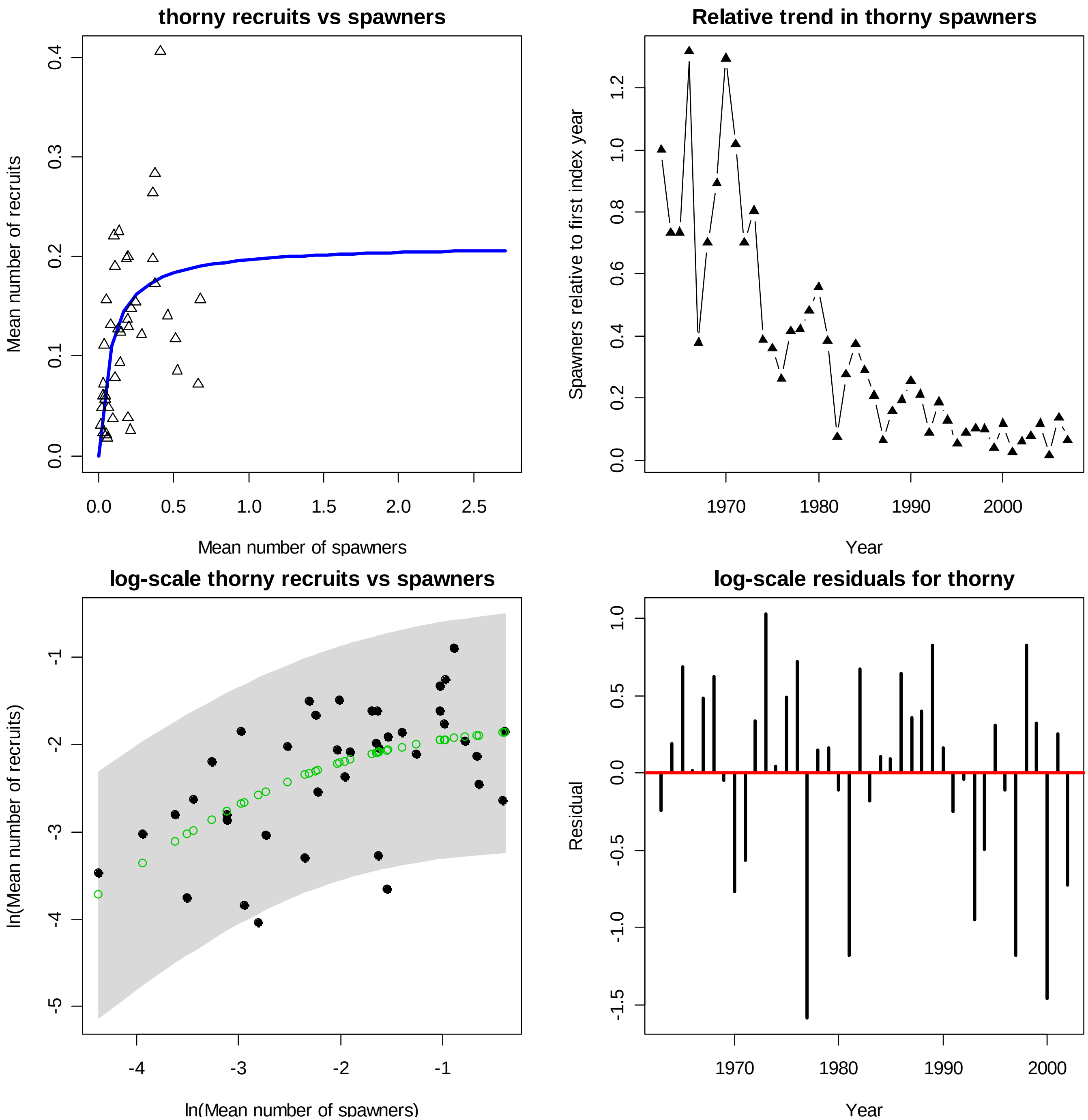

Figure 2. Diagnostic plots for **thorny** skate: observed (open triangles) versus predicted mean number of recruits (top left), observed time series of spawners scaled by the first observation ($S_y/S_{y=1}$) (top right), log-scale fit of observed (solid circles) to predicted (open circles) number of recruits/tow with shaded 95% confidence interval (bottom left), and standardized log-scale residuals (bottom right).

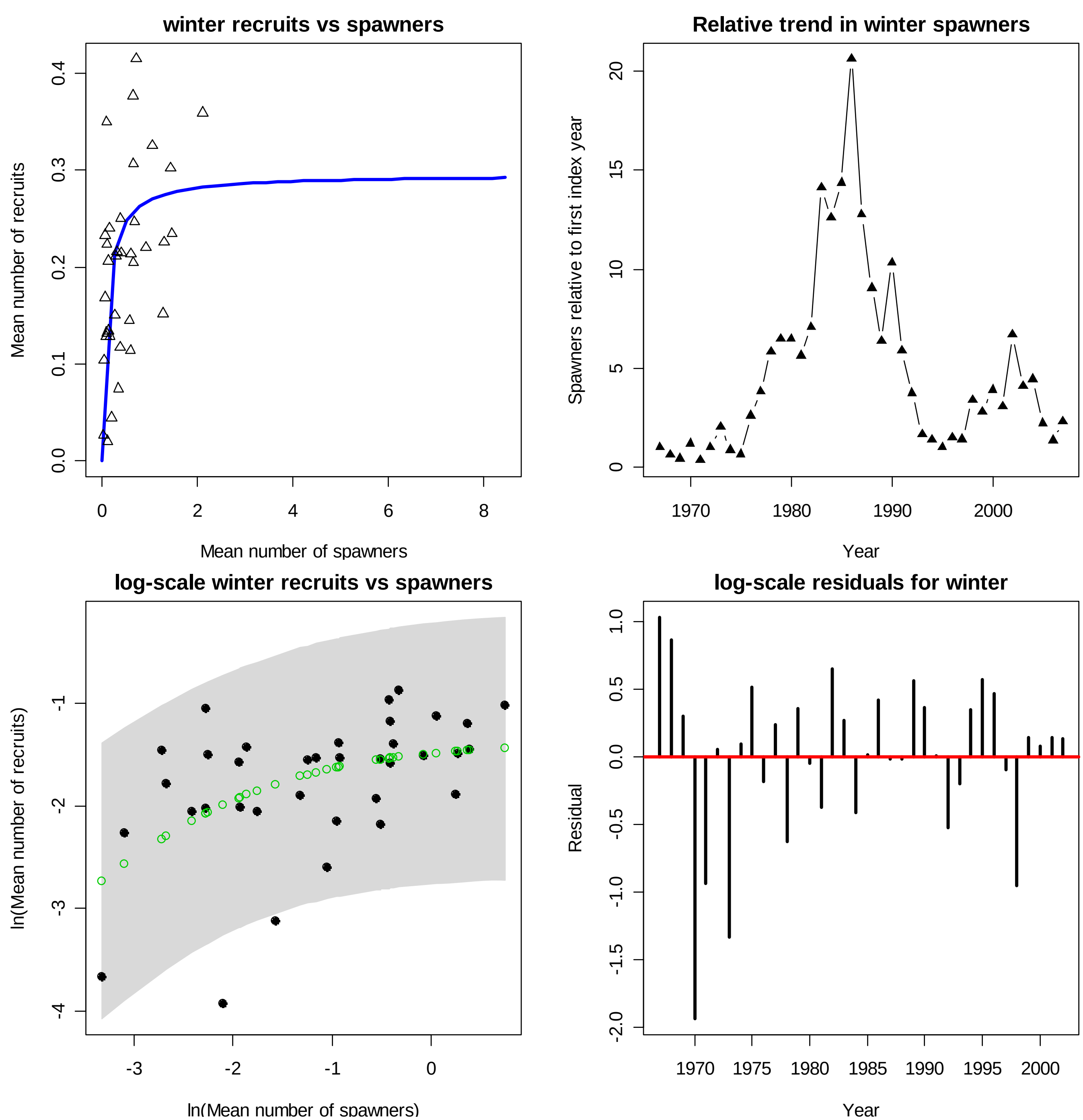

Figure 3. Diagnostic plots for **winter** skate: observed (open triangles) versus predicted mean number of recruits (top left), observed time series of spawners scaled by the first observation ($S_y/S_{y=1}$) (top right), log-scale fit of observed (solid circles) to predicted (open circles) number of recruits/tow with shaded 95% confidence interval (bottom left), and standardized log-scale residuals (bottom right).

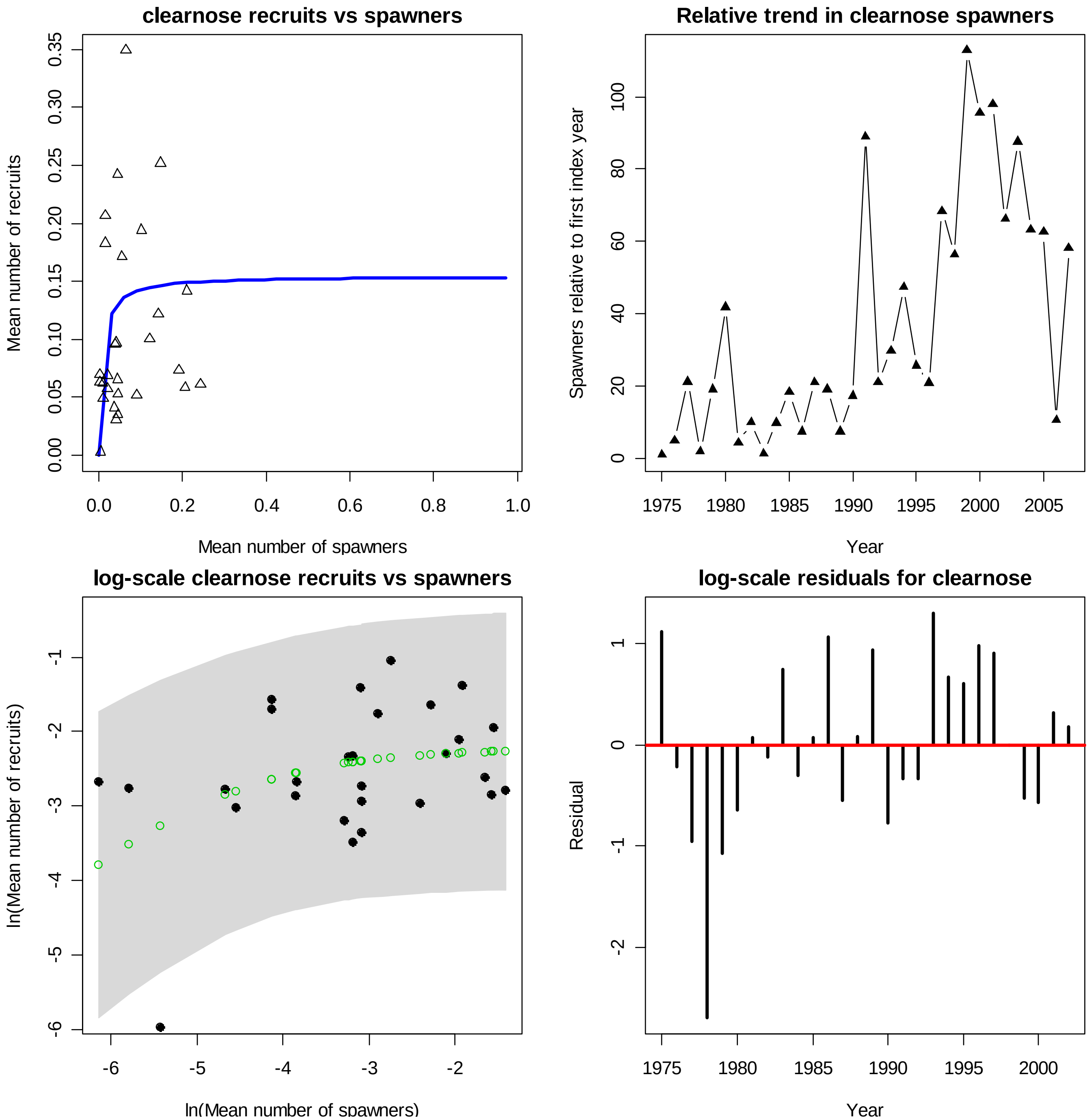

Figure 4. Diagnostic plots for **clearnose** skate: observed (open triangles) versus predicted mean number of recruits (top left), observed time series of spawners scaled by the first observation ($S_y/S_{y=1}$) (top right), log-scale fit of observed (solid circles) to predicted (open circles) number of recruits/tow with shaded 95% confidence interval (bottom left), and standardized log-scale residuals (bottom right).

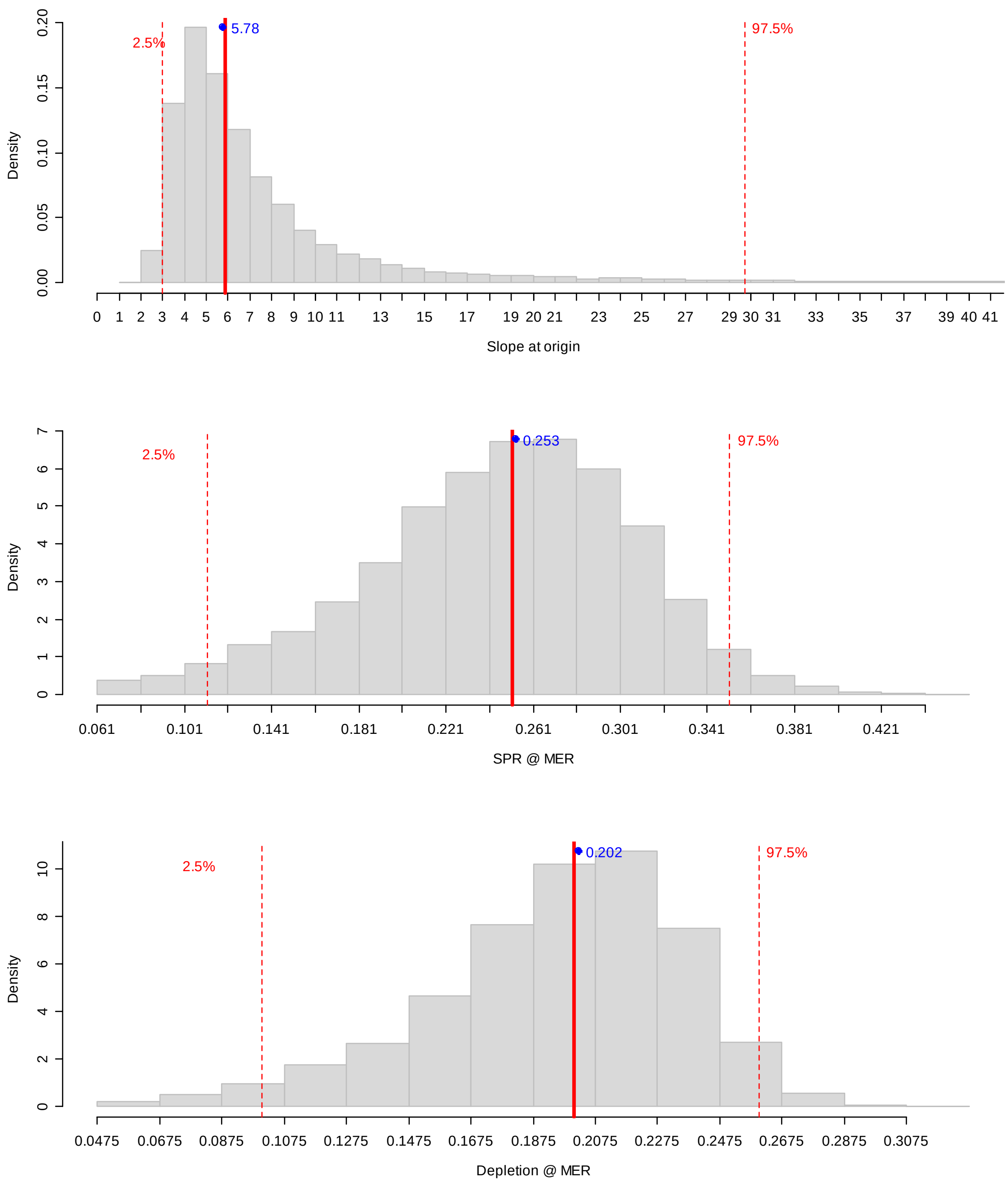

Figure 5. Posterior distributions from MCMC for the slope at the origin (top), SPR_{MER} (middle), and depletion at MER(bottom) for **barndoor** skate. In each plot, the point estimate is indicated by a solid circle and that value is beside the point. The median of the posterior is indicated by a solid vertical red line, while the 2.5th and 97.5th percentiles are indicated by dashed vertical red lines.

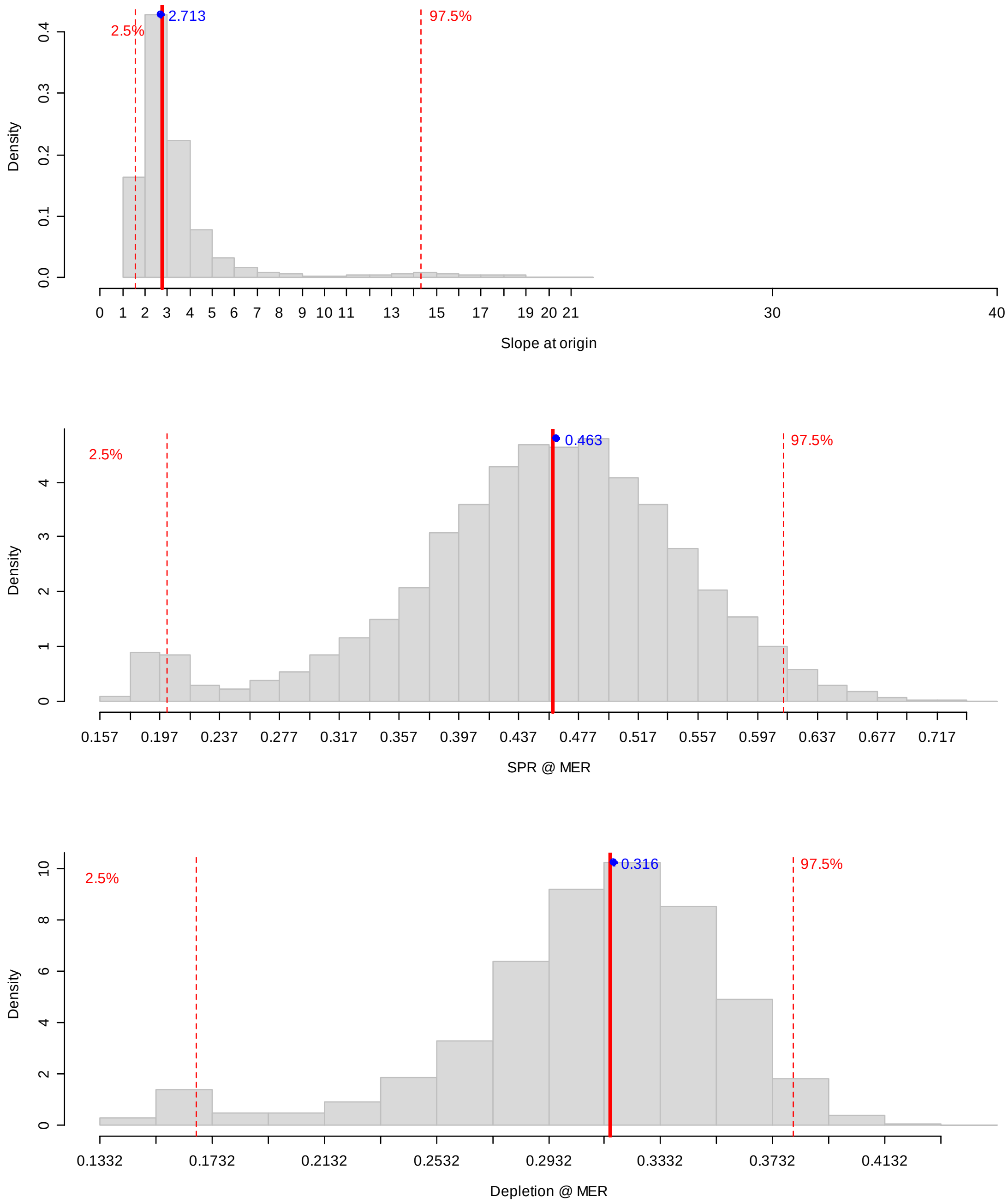

Figure 6. Posterior distributions from MCMC for the slope at the origin (top), SPR_{MER} (middle), and depletion at MER(bottom) for **thorny** skate. In each plot, the point estimate is indicated by a solid circle and that value is beside the point. The median of the posterior is indicated by a solid vertical red line, while the 2.5th and 97.5th percentiles are indicated by dashed vertical red lines.

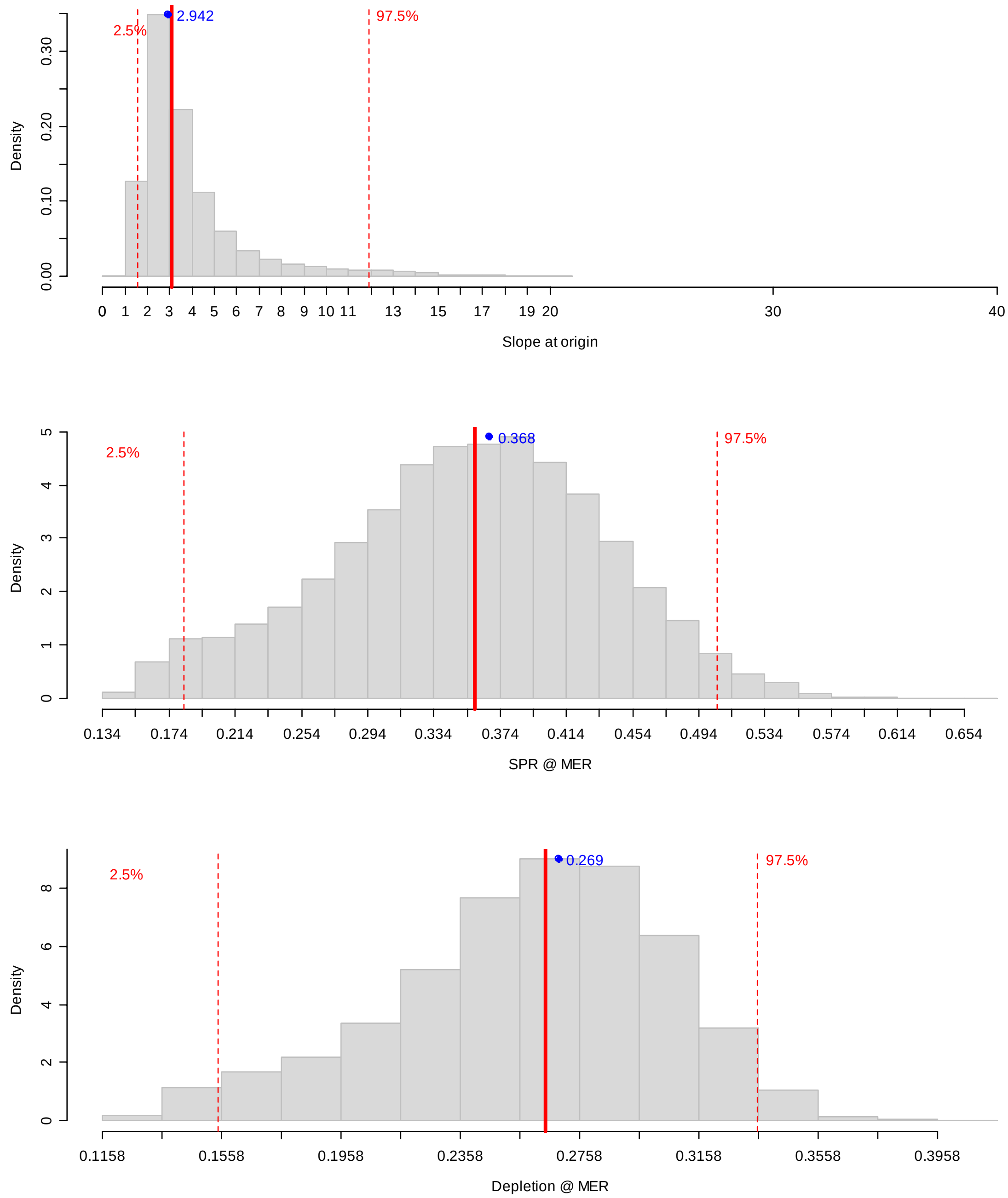

Figure 7. Posterior distributions from MCMC for the slope at the origin (top), SPR_{MER} (middle), and depletion at MER(bottom) for **winter** skate. In each plot, the point estimate is indicated by a solid circle and that value is beside the point. The median of the posterior is indicated by a solid vertical red line, while the 2.5^{th} and 97.5^{th} percentiles are indicated by dashed vertical red lines.