

Quantifying the Tradeoff Between Precaution
and Yield in the U.S. Sea Scallop Fishery

Deborah R. Hart

Northeast Fisheries Science Center

National Marine Fisheries Service

166 Water St.

Woods Hole MA 02543 USA

Email: Deborah.Hart@noaa.gov

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Abstract

1
2 Fishery reference points in the U.S. sea scallop fishery are set using yield
3 per recruit analysis. Because of uncertainties in the parameters used in this
4 analysis, the estimated reference points are uncertain. For this reason, it
5 is often argued that target fishing mortality rates should be less than the
6 calculated reference points in order to reduce the risk of overfishing. However,
7 precautionary management also can reduce yield by fishing at suboptimal
8 rates. Here, I use Monte-Carlo simulations to quantify the tradeoff between
9 overfishing risk and loss in yield per recruit. At fishing mortalities near F_{MAX} ,
10 the fishing mortality where maximum yield per recruit is obtained, reducing
11 fishing mortality obtains a substantial reduction in the risk of overfishing at
12 little cost of lost yield per recruit. At lower fishing mortality rates, however,
13 the marginal benefit in terms of reduced fishing mortality risk from further
14 reductions in fishing mortality becomes less, and the cost in reduced yield
15 per recruit becomes greater. If implementation uncertainty is added to the
16 analysis, the risk of overfishing as well the loss of yield per recruit is increased,
17 except at F_{MAX} .

18 Introduction

19 Fishery reference points are uncertain because the models that generate them
20 depend on parameters that are themselves uncertain. For this reason, it has
21 long been recommended that reference points be set on a precautionary basis,
22 so as to minimize the risk of overfishing. This approach has been codified into
23 U.S. law in 1996 and 2006 by revisions to the Magnuson-Stevens fishery act.
24 However, reducing fishing mortality below F_{MSY} will, by definition, reduce the
25 expected yields that can be obtained from the fishery. While precaution gives
26 benefits in that it reduces the risk of overfishing and its concomitant impacts
27 on the marine ecosystem, it also has a cost in that it reduces expected yield.
28 The purpose of this paper is to explore these tradeoffs in setting reference
29 points for the U.S. sea scallop, *Placopecten magellanicus*, fishery.

30 Because stock-recruit relationships for sea scallops are not well defined
31 (and are presumably saturated at current and future biomass levels), ref-
32 erence points for sea scallops have been set using yield per recruit analysis,
33 using F_{MAX} as a proxy for F_{MSY} . The most recent sea scallop stock assessment
34 (NEFSC 2007) estimated $F_{\text{MAX}} = 0.24$ on Georges Bank, $F_{\text{MAX}} = 0.36$ in the
35 Mid-Atlantic, and $F_{\text{MAX}} = 0.29$ for the fishery overall.

36 Uncertainties in yield per recruit analysis can be assessed by estimating a
37 probability distribution for each of the input parameters and then repeatedly
38 drawing parameters at random from these distributions and performing yield
39 per recruit analysis using these choices (Restrepo and Fox 1988). By repeat-
40 ing this procedure a large number of times, the probability distribution of
41 F_{MAX} and the expected yield per recruit at a given fishing mortality can be
42 estimated. From this, the probability of overfishing at a fishing mortality F
43 as well as the loss in yield per recruit incurred by fishing at F rather than
44 F_{MAX} can be calculated.

45 Besides the uncertainties in the reference points, there is implementation
46 error in that the fishing mortality target intended by managers may not be

47 realized precisely, and the actual fishing mortality may be greater or less
48 than that intended by management. The effect of such errors will also be
49 discussed here.

50 **Methods**

51 **Monte-Carlo yield per recruit analysis**

52 A description of basic length-based yield per recruit model used in this analy-
53 sis can be found in Hart (2003). The yield per recruit calculations depend
54 on a number of parameters which each carry a level of uncertainty:

- 55 (1) Von Bertalanffy growth parameters K and L_∞
- 56 (2) Shell height/meat weight parameters a and b
- 57 (3) Natural mortality rate M
- 58 (4) Fishery selectivity parameters α and β
- 59 (5) The cull size of the catch and the fraction of discards that survive
- 60 (6) The level of incidental fishing mortality, i.e., non-catch mortality caused
61 by fishing.

62
63 Each of these parameters were assigned a probability distribution reflect-
64 ing their level of uncertainty, as discussed below. For each iteration, choices
65 for each of these parameters were drawn from their distributions, and then
66 a yield per recruit analysis was performed. This was repeated for $n = 10000$
67 iterations for both regions (Georges Bank and Mid-Atlantic) and the results
68 collected. Of particular interest were the expected yield per recruit at a given
69 fishing mortality F and the probability that overfishing would be occurring
70 if fishing mortality was F . The expected yield per recruit was calculated
71 simply as the average of the yield per recruit of each run. The probability of
72 overfishing was estimated as the number of runs for which $F_{\text{MAX}} < F$ divided
73 by the total number of runs.

74 The estimates of three sets of these parameters (K and L_∞ , a and b , and
75 α and β) are confounded, as reflected by a strong correlation between the
76 estimates. For example, a growth curve with a given K and L_∞ resembles
77 one with a slightly smaller K and larger L_∞ , implying a negative correlation
78 between the estimates of the two parameters. In these cases, each parameter
79 pair was simulated as correlated normals. In other cases, gamma distribu-
80 tions were used.

81 The analyses were done separately in each area (Georges Bank and Mid-
82 Atlantic). Expected yields were combined assuming that each area is equally
83 productive. This is approximately correct over the last 25 years, though
84 Georges Bank was more productive over a longer time period, and the Mid-
85 Atlantic more productive in recent years. Calculating the probability of
86 overfishing of the combined resource requires additional assumptions regard-
87 ing the correlation of parameters in the two regions. It would seem likely
88 that a positive correlation exists, e.g., if the natural mortality estimate of
89 0.1 was underestimated in one region, it is likely that it is also in the other.
90 For that reason, it is assumed here that the corresponding parameters in
91 the two regions are correlated with a correlation of 1. If this correlation is
92 smaller, the variability between the regions would partially cancel, and the
93 probability of overfishing would be somewhat less than calculated here.

94 **Probability distributions for the simulated parameters**

95 The mean, standard error and correlation (when applicable) for each of the
96 simulated parameters is given in Table 1. These estimates were taken from
97 the latest sea scallop stock assessment (NEFSC 2007) or from the litera-
98 ture. When standard errors were not available, they were estimated using
99 reasonable judgement. Details on each of these parameters is given below.

100 **Growth parameters K and L_∞ .** These parameters were estimated using a
101 linear mixed-effects model based on the reading of sea scallop rings from shells

102 collected during the 2001-2006 NEFSC sea scallop surveys (NEFSC 2007).
103 These estimates were recently revised by using a slightly refined model and
104 one additional year of data (Hart and Chute 2009). In order to conform to
105 the NEFSC (2007) reference points, the growth parameters estimated there
106 were used, rather than the updated ones. The difference between these is in
107 any case minimal.

108 As discussed above, K and L_∞ were simulated as negatively correlated
109 normals, with their mean, variance and covariance as estimated in NEFSC
110 (2007). The standard errors of K and L_∞ are very small due to the large
111 amount of data available. The true uncertainty may be greater than this
112 “statistical uncertainty” because of model uncertainties. For example, von
113 Bertalanffy growth appears to well approximate sea scallop growth, but is
114 probably not exactly correct. Such uncertainties are not reflected in the
115 standard errors of the parameters. However, simulations indicate that the
116 mixed-effects model is robust to a number of uncertainties, and likely esti-
117 mates the mean growth parameters to within 1% of its true value (Hart and
118 Chute 2009).

119 **Shell height/meat weight relationships.** Meat weight W at shell height
120 H is calculated using a formula of the form:

$$121 \qquad W = \exp(a + b \ln(H)) \qquad (1)$$

122 The parameters a and b were estimated during the last sea scallop bench-
123 mark assessment (NEFSC 2007) using a generalized mixed-effects model
124 (GLMM) based on data collected during the 2001-2006 NEFSC annual sea
125 scallop surveys. This analysis was used to obtain estimates of means, vari-
126 ances, and covariances of the parameters (Table 1). Similar to the growth
127 parameters, the estimates of a and b are somewhat confounded, so that they
128 have a strong negative correlation. This means that the predicted meat
129 weight at a given shell height carries less uncertainty than it would appear

130 from the variances of the individual parameters.

131 Meat weights vary seasonally, with the greatest meat weights during the
132 late spring and early summer. Meat weights drop considerably after the later
133 summer/early fall spawn and stay low until the spring. These patterns were
134 documented in NEFSC (2007) using observer data. Observers weigh scallop
135 meats in aggregate, so that it is not possible to distinguish which of the
136 shell height/meat weight parameters change seasonally. However, general
137 allometric principles suggest that most of the variation is in the intercept a
138 rather than the slope (or power) parameter b . Haynes (1966) constructed a
139 number of monthly shell height/meat weight relationships, and did not find
140 any significant trend in the slopes. Thus, it was assumed in NEFSC (2007)
141 that all the seasonal variation in meat weights was due to variability in a . If
142 this is the case, seasonality would not affect the F_{MAX} reference point. For
143 this reason, seasonal variability was not considered a source of uncertainty
144 for this analysis.

145 **Natural mortality M .** Like most stocks, natural mortality is one of the
146 most uncertain parameters. However, dead “clapper” scallops (dead scallop
147 shells still attached at the hinge) are an indicator of recent natural mortality,
148 due to such causes as disease, high temperatures and sea star predation. The
149 clappers separate some time after death because of hinge degeneration. At
150 equilibrium, the rate of clappers being produced, ML , where L is the number
151 of live scallops, must equal the rate of loss of clappers C/S , where S is the
152 mean clapper separation time and C is the number of clappers. Solving this
153 for M gives:

$$154 \quad M = \frac{1}{S} \frac{C}{L} \quad (2)$$

155 so that natural mortality is proportional to the ratio of clappers to live scal-
156 lops.

157 Merrill and Posgay (1964) used this idea to estimate natural mortality.
158 They estimated the clapper ratio $C/L = 0.0662$, and the mean separation

159 time $S = 33$ weeks $= 33/52$ years, to estimate an annual natural mortality
 160 rate of $(52/33) * 0.0662 = 0.104 \approx 0.1$. Probably the greatest uncertainty in
 161 this calculation is the mean separation time S . For example, Dickie (1955)
 162 estimated S to be 100 days (14.3 weeks). I assumed S was distributed as
 163 a gamma random variable, with mean 33 weeks and standard deviation 15
 164 weeks. The resulting distribution of M has the desirable characteristic of
 165 being skewed to the right. This makes sense since, for example, a natural
 166 mortality of $M = 0.2$ is possible, but an $M = 0$, or even close to zero, is not.
 167 Note that because S appears in the denominator of (2), the mean value of
 168 M is not equal to applying equation (2) with the mean value of S , so that
 169 the original calculation of Merrill and Posgay (1964) was biased.

170 **Fishery selectivity.** Fishery selectivity s was estimated using an ascending
 171 logistic curve of the form:

$$172 \quad s = \frac{1}{1 + \exp(\alpha - \beta H)} \quad (3)$$

173 where H is shell height. The mean, variances, and correlation of the α and
 174 β parameters were estimated based on CASA model runs from the last sea
 175 scallop assessment during the most recent time period. Note that fishery
 176 selectivity reflects targeting as well as gear selectivity.

177 **Discard mortality.** Sea scallops likely tolerate discarding fairly well, pro-
 178 vided they are returned to the water relatively promptly and they are not
 179 damaged by the capture process or their time on deck. Further uncertainty
 180 occurs in the summertime in the Mid-Atlantic, where summer SST exceeds
 181 the thermal tolerance of sea scallops. Discard mortality was estimated at
 182 20% in the last assessment, but there is little confidence in this number.
 183 Here, discard mortality was simulated as a gamma distribution, with a mean
 184 of 0.2 and a standard deviation of 0.15.

185 **Incidental fishing mortality.** Incidental fishing mortality occurs when
 186 scallops are killed but not captured by the gear. Let F_L be the landed fishing

187 mortality rate and F_I be the rate of incidental fishing mortality. F_I should
 188 be proportional to F_L , say $F_I = iF_L$. Based on the studies of Caddy (1973)
 189 and Serchuk and Murawski (1989), i was estimated as 0.15 on Georges Bank
 190 and 0.04 in the Mid-Atlantic by NEFSC(2007). Because of the considerable
 191 uncertainty in these numbers, i was simulated here with a gamma distribution
 192 with these means and coefficients of variation of 0.75.

193 **Incorporating management uncertainty**

194 The actual fishing mortality realized may be different than the target fishing
 195 mortality set by managers. Thus, for a fixed target fishing mortality F_{TARGET} ,
 196 the actual fishing mortality F_a is a random variable with density function
 197 $p(F)$. Denote by $Y(F)$ the expected yield per recruit obtained by fishing at
 198 F , and $Y_t(F)$ the expected yield per recruit obtained by setting the target
 199 fishing mortality at F . Note that these will be different, even if the process of
 200 setting the management targets is unbiased because yield per recruit curves
 201 are non-linear. The expected yield per recruit obtained from setting the
 202 target at F_{TARGET} is:

$$203 \quad Y_t(F_{\text{TARGET}}) = \int_0^{\infty} p(F)Y(F) dF. \quad (4)$$

204 For these analyses, I assumed that the density function $p(F)$ is normal (in
 205 principle, this needs to be truncated at 0, but in practice there is negligible
 206 probability that $F < 0$) with mean F_{TARGET} and standard deviation σ . The
 207 integral was estimated by discretization with a step size of 0.01.

208 It remains to estimate the standard deviation σ . The CASA stock assess-
 209 ment model generally estimates fishing mortalities with errors of between 0.01
 210 to 0.02. However, these are estimates of past fishing mortalities, obtained
 211 when all the information is available. Managers set effort and/or quota levels
 212 based on forecasts that must contain more uncertainty than stock assessment
 213 estimates of prior years. The SAMS projection model used for forecasts in

214 the scallop fishery typically gives uncertainty in fishing mortalities of about
215 $\sigma = 0.04$ for short-term forecasts, based on bootstraps of initial conditions
216 and stochastic recruitment variability. This estimate does not include “model
217 error” such as uncertainties in model parameters or changes in fishing prac-
218 tices. If this type of error is of similar magnitude and independent from the
219 stochastic error already quantified by the SAMS model, the total implemen-
220 tation error is about $0.04\sqrt{2} \approx 0.06$. The analysis was conducted both with
221 $\sigma = 0.04$ as a lower bound and $\sigma = 0.06$.

222 Results and Discussion

223 The tradeoffs between probability of overfishing and losses in expected yield
224 are shown in Table 2 and Figure 1. Maximal expected yield per recruit
225 are obtained at somewhat higher (by about 0.07) fishing mortalities than
226 calculated in the last sea scallop assessment (NEFSC 2007). There are two
227 reasons for this. First, even though the Merrill and Posgay (1964) estimates
228 were used as the expected value of the clapper ratio and separation time
229 for the clappers, the mean natural mortality was about 0.13, rather than
230 the 0.1 estimated by Merrill and Posgay (1964), due to the uncertainty in
231 the denominator of equation (2). Secondly, the yield per recruit curve is
232 asymmetric, with a greater slope (in absolute magnitude) to the left of F_{MAX}
233 than to the right. As a result, expected yield per recruit will be optimized
234 by fishing at a level slightly greater than the point estimate of F_{MAX} .

235 Reducing fishing mortality near F_{MAX} produces considerable benefits (in
236 terms of reduced risk of overfishing) at only a small cost (reduced expected
237 yield per recruit). However, as fishing mortality is further reduced, benefits
238 are reduced and costs increase. Basic cost/benefit theory states that the
239 point of optimal cost/benefit will occur where the marginal benefit equals
240 the marginal cost. The difficulty in applying this theory is that costs and

241 benefits are in incommensurate quantities, so that the value of a decreased
242 risk of overfishing compared to a loss in expected yield is subjective. Thus,
243 some judgement is required to decide the appropriate balance. The scallop
244 PDT suggested that the ABC fishing mortality should be set where the risk
245 of overfishing is 0.25, or where the loss of yield per recruit is 1% less than
246 optimal, whichever is less. According to Table 2, this would result in an ABC
247 fishing mortality target of 0.28. While this value is reasonable, arguments
248 can be made for just about any target between 0.2 and 0.3.

249 Performing similar analyses, but using target fishing mortality instead of
250 actual fishing mortality, indicates that at lower fishing mortalities, imple-
251 mentation error increases both the risk of overfishing and the loss of yield
252 per recruit due to precaution (Tables 3 and 4; Figures 2 and 3).

253 It is also of interest when setting the target is to calculate the proba-
254 bility of exceeding the ABC fishing mortality, since this triggers “account-
255 ability measures.” Because implementation error is assumed to be normally
256 distributed, this can be calculated simply from a table of (inverse) normal
257 probabilities (Table 5).

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Table 1. Mean, standard error, and distributions of parameters used in the yield per recruit analysis.

(a) Georges Bank

Parameter	Purpose	Mean	S.E.	Corr.	Distribution
K	Growth	0.375	0.002	-0.6	Corr. Normal
L_∞	Growth	146.5	0.3	-0.6	Corr. Normal
a	SH/MW	-10.70	0.27	-0.998	Corr. Normal
b	SH/MW	2.942	0.055	-0.998	Corr. Normal
S	Nat. mort.	33/52 y	15/52 y		Gamma
α	Selectivity	25.24	8.69	0.998	Corr. Normal
β	Selectivity	0.23	0.08	0.998	Corr. Normal
F_D	Disc. mort.	0.2	0.15		Gamma
i	Incid. mort.	0.15	0.11		Gamma

(b) Mid-Atlantic

Parameter	Purpose	Mean	S.E.	Corr.	Distribution
K	Growth	0.495	0.004	-0.6	Corr. Normal
L_∞	Growth	131.6	0.4	-0.6	Corr. Normal
a	SH/MW	-12.01	0.15	-0.997	Corr. Normal
b	SH/MW	3.22	0.05	-0.997	Corr. Normal
S	Nat. mort.	33/52 y	15/52 y		Gamma
α	Selectivity	21.67	2.77	0.998	Corr. Normal
β	Selectivity	0.214	0.03	0.998	Corr. Normal
F_D	Disc. mort.	0.2	0.15		Gamma
i	Incid. mort.	0.04	0.03		Gamma

Table 2. Probability of overfishing (POF) and loss of yield per recruit (percentage loss compared to maximal) for sea scallops in Georges Bank, the Mid-Atlantic, and overall.

Georges Bank			Mid-Atlantic			Overall		
F	POF	%Loss	F	POF	%Loss	F	POF	%Loss
0.10	0	23	0.20	0.003	7.7	0.15	0	12.33
0.11	0	19.7	0.21	0.007	6.8	0.16	0	10.62
0.12	0	16.7	0.22	0.012	5.9	0.17	0.003	9.13
0.13	0	14.2	0.23	0.021	5.1	0.18	0.005	7.81
0.14	0	12.1	0.24	0.033	4.4	0.19	0.01	6.66
0.15	0.001	10.2	0.25	0.050	3.8	0.20	0.02	5.65
0.16	0.004	8.6	0.26	0.066	3.2	0.21	0.038	4.77
0.17	0.011	7.2	0.27	0.084	2.7	0.22	0.058	4
0.18	0.022	5.9	0.28	0.108	2.3	0.23	0.083	3.32
0.19	0.04	4.9	0.29	0.132	1.9	0.24	0.108	2.74
0.20	0.06	4	0.30	0.159	1.6	0.25	0.13	2.23
0.21	0.087	3.2	0.31	0.186	1.3	0.26	0.158	1.79
0.22	0.119	2.6	0.32	0.215	1.0	0.27	0.189	1.41
0.23	0.154	2	0.33	0.244	0.8	0.28	0.225	1.09
0.24	0.191	1.5	0.34	0.277	0.6	0.29	0.254	0.82
0.25	0.226	1.2	0.35	0.304	0.5	0.30	0.29	0.6
0.26	0.263	0.8	0.36	0.333	0.3	0.31	0.333	0.41
0.27	0.303	0.6	0.37	0.363	0.2	0.32	0.355	0.27
0.28	0.341	0.4	0.38	0.388	0.1	0.33	0.385	0.16
0.29	0.381	0.2	0.39	0.416	0.1	0.34	0.418	0.08
0.30	0.418	0.1	0.40	0.443	0.0	0.35	0.448	0.03
0.31	0.449	0	0.41	0.467	0.0	0.36	0.483	0
0.32	0.484	0	0.42	0.490	0.0	0.37	0.51	0
0.33	0.515	0	0.43	0.512	0.0	0.38	0.535	0.02
0.34	0.54	0	0.44	0.535	0.0	0.39	0.555	0.06
0.35	0.568	0.1	0.45	0.557	0.0	0.40	0.578	0.11

Table 3. Probability of overfishing (POF) and loss of yield per recruit (percentage loss compared to maximal) for sea scallops in Georges Bank, the Mid-Atlantic, and overall, with respect to target fishing mortality rates, assuming $\sigma = 0.04$ implementation uncertainty.

Georges Bank			Mid-Atlantic			Overall		
F_{TARGET}	POF	%Loss	F_{TARGET}	POF	%Loss	F_{TARGET}	POF	%Loss
0.10	0.001	27.7	0.20	0.015	8.7	0.15	0.016	14.06
0.11	0.002	23.6	0.21	0.022	7.6	0.16	0.022	12.12
0.12	0.004	20.0	0.22	0.030	6.6	0.17	0.029	10.43
0.13	0.007	17.0	0.23	0.040	5.8	0.18	0.038	8.96
0.14	0.012	14.4	0.24	0.052	5.0	0.19	0.049	7.66
0.15	0.018	12.2	0.25	0.067	4.3	0.20	0.062	6.51
0.16	0.027	10.3	0.26	0.083	3.7	0.21	0.076	5.50
0.17	0.038	8.7	0.27	0.102	3.2	0.22	0.093	4.63
0.18	0.053	7.3	0.28	0.122	2.7	0.23	0.111	3.86
0.19	0.070	6.1	0.29	0.145	2.3	0.24	0.131	3.20
0.20	0.091	5.0	0.30	0.169	1.9	0.25	0.153	2.62
0.21	0.114	4.1	0.31	0.194	1.6	0.26	0.177	2.12
0.22	0.141	3.4	0.32	0.220	1.3	0.27	0.201	1.69
0.23	0.170	2.7	0.33	0.247	1.1	0.28	0.227	1.33
0.24	0.201	2.2	0.34	0.275	0.9	0.29	0.254	1.02
0.25	0.234	1.7	0.35	0.302	0.7	0.30	0.281	0.76
0.26	0.268	1.3	0.36	0.330	0.5	0.31	0.309	0.55
0.27	0.303	1.0	0.37	0.357	0.4	0.32	0.337	0.37
0.28	0.337	0.8	0.38	0.384	0.3	0.33	0.364	0.24
0.29	0.372	0.6	0.39	0.410	0.2	0.34	0.392	0.14
0.30	0.406	0.4	0.40	0.435	0.2	0.35	0.419	0.06
0.31	0.439	0.3	0.41	0.460	0.1	0.36	0.445	0.02
0.32	0.471	0.3	0.42	0.484	0.1	0.37	0.470	0.00
0.33	0.501	0.2	0.43	0.507	0.1	0.38	0.495	0.00
0.34	0.530	0.2	0.44	0.529	0.0	0.39	0.518	0.03
0.35	0.558	0.3	0.45	0.551	0.0	0.40	0.541	0.07

Table 4. Probability of overfishing (POF) and loss of yield per recruit (percentage loss compared to maximal) for sea scallops in Georges Bank, the Mid-Atlantic, and overall, with respect to target fishing mortality rates, assuming $\sigma = 0.06$ implementation uncertainty.

Georges Bank			Mid-Atlantic			Overall		
F_{TARGET}	POF	%Loss	F_{TARGET}	POF	%Loss	F_{TARGET}	POF	%Loss
0.1	0.006	27.5	0.2	0.033	9.4	0.15	0.016	16.22
0.11	0.009	25.2	0.21	0.042	8.2	0.16	0.022	13.71
0.12	0.014	22.9	0.22	0.053	7.2	0.17	0.029	11.77
0.13	0.019	20.5	0.23	0.064	6.3	0.18	0.038	10.09
0.14	0.026	19.4	0.24	0.078	5.4	0.19	0.049	8.63
0.15	0.034	16.7	0.25	0.093	4.7	0.2	0.062	7.36
0.16	0.044	14.1	0.26	0.110	4.1	0.21	0.076	6.25
0.17	0.057	11.9	0.27	0.129	3.5	0.22	0.093	5.28
0.18	0.071	10.1	0.28	0.149	3.0	0.23	0.111	4.42
0.19	0.088	8.5	0.29	0.170	2.5	0.24	0.131	3.67
0.2	0.107	7.1	0.3	0.192	2.2	0.25	0.153	3.03
0.21	0.128	5.9	0.31	0.216	1.8	0.26	0.177	2.47
0.22	0.151	4.9	0.32	0.240	1.5	0.27	0.201	1.99
0.23	0.176	4.1	0.33	0.265	1.3	0.28	0.227	1.58
0.24	0.202	3.3	0.34	0.290	1.0	0.29	0.254	1.23
0.25	0.231	2.7	0.35	0.316	0.9	0.3	0.281	0.93
0.26	0.260	2.2	0.36	0.341	0.7	0.31	0.309	0.68
0.27	0.291	1.8	0.37	0.367	0.6	0.32	0.337	0.48
0.28	0.321	1.4	0.38	0.392	0.4	0.33	0.365	0.32
0.29	0.353	1.2	0.39	0.417	0.3	0.34	0.392	0.20
0.3	0.384	0.9	0.4	0.441	0.3	0.35	0.419	0.11
0.31	0.415	0.8	0.41	0.465	0.2	0.36	0.445	0.05
0.32	0.445	0.6	0.42	0.489	0.2	0.37	0.470	0.01
0.33	0.475	0.5	0.43	0.511	0.1	0.38	0.495	0.00
0.34	0.504	0.4	0.44	0.533	0.1	0.39	0.519	0.01
0.35	0.532	0.4	0.45	0.554	0.1	0.4	0.541	0.04

Table 5. Risk of exceeding the ABC and hence encountering accountability measures at various reductions in target fishing mortalities below the ABC fishing mortality.

Reduction in F	$P(F > F_{ABC})$ $\sigma = 0.04$	$P(F > F_{ABC})$ $\sigma = 0.06$
0.01	0.401	0.434
0.02	0.309	0.369
0.03	0.227	0.309
0.04	0.159	0.252
0.05	0.106	0.202
0.06	0.067	0.159
0.07	0.040	0.122
0.08	0.023	0.091
0.09	0.012	0.067
0.10	0.006	0.048
0.11	0.003	0.033
0.12	0.001	0.023

Figure legends

Figure 1. The probability of overfishing (solid) and loss in yield per recruit (dashed) for (a) Georges Bank, (b) Mid-Atlantic and (c) overall, as a function of true fishing mortality.

Figure 2. Figure 1. The probability of overfishing (solid) and loss in yield per recruit (dashed) for (a) Georges Bank, (b) Mid-Atlantic and (c) overall, as a function of target fishing mortality with implementation error $\sigma = 0.04$.

Figure 3. The probability of overfishing (solid) and loss in yield per recruit (dashed) for (a) Georges Bank, (b) Mid-Atlantic and (c) overall, as a function of target fishing mortality with implementation error $\sigma = 0.06$.

Figure 1

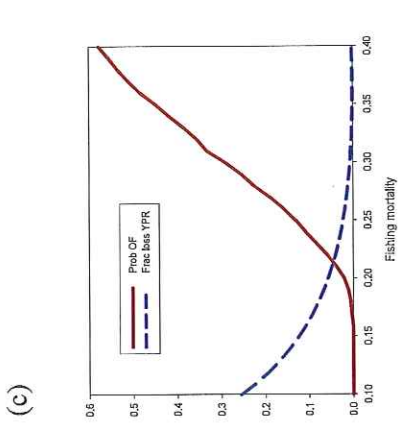
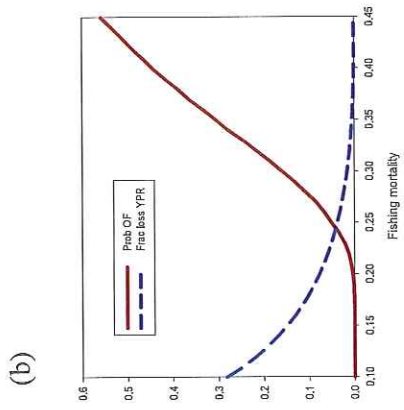
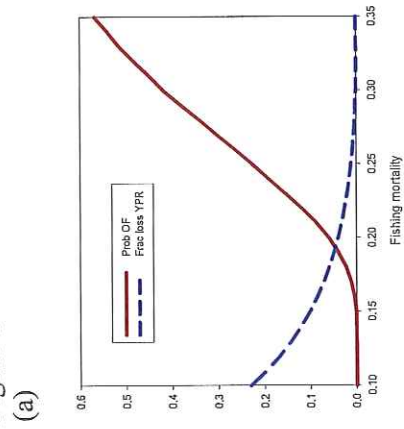


Figure 2

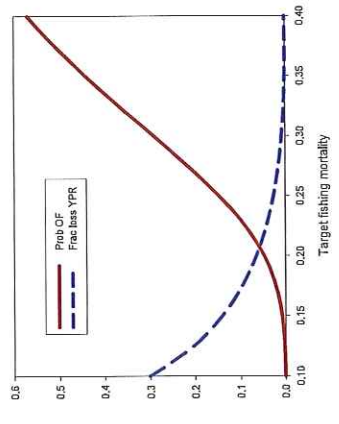
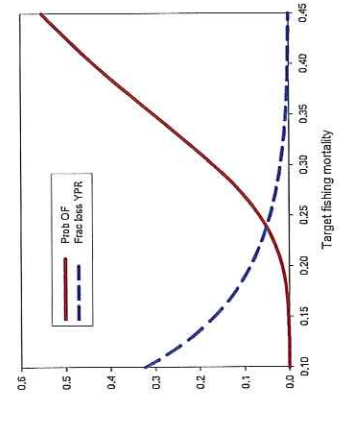
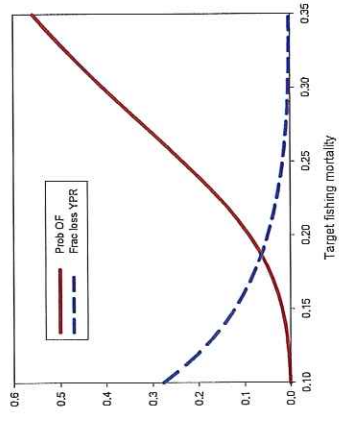
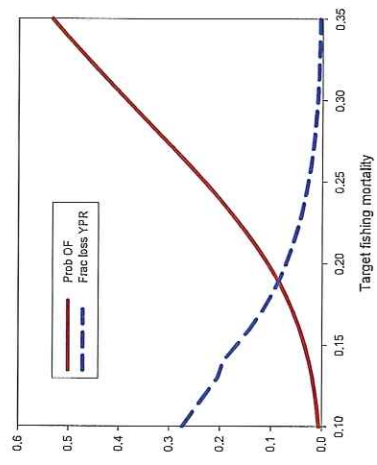
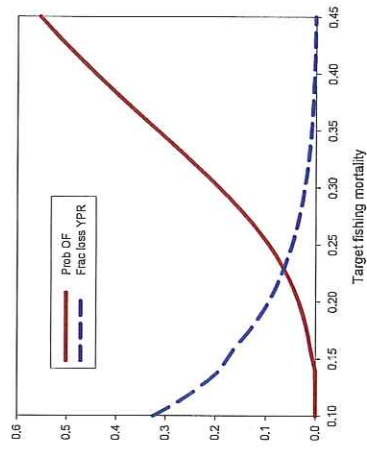


Figure 3
(a)



(b)



(c)

