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Quantifying the tradeoff between precaution and yield in fishery reference points

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A method using Monte Carlo simulations for estimating fishery reference points that accounts for parameter uncertainty is presented. Uncertainties in the input parameters of yield-per-recruit and stock-recruit analyses are propagated to estimate uncertainty in reference points such as F_{MSY}. These uncertainties are used to evaluate the tradeoffs between the risks of overfishing and stock collapse, and the cost of reduced expected yield due to setting fishing mortality below F_{MSY}. At fishing mortalities near F_{MSY}, reduction in fishing mortality substantially decreases the probability of overfishing and stock collapse in exchange for slightly reduced expected yield. At lower fishing mortality rates, the marginal benefit (in terms of lessened risk of overfishing and stock collapse) from further reductions in fishing mortality is less, and the cost in forgone yield is greater. Less resilient "low steepness" stocks require additional precaution due to the risk of complete population collapse. Marine protected areas can also reduce risks of collapse, but at a higher cost in terms of expected yield than effort reduction. Implementation uncertainty (i.e. uncertainty in achieving a fishing mortality target) increases the risk of overfishing as well the loss of yield due to precaution, except at fishing mortalities near or above F_{MSY}.

Keywords: fishery reference points, marine protected areas, MSY, stochastic model, risk assessment, scallop, Placopecten magellanicus.

Introduction

Fishery reference points are uncertain because the models and parameters that generate them are themselves uncertain. For this reason, it has long been recommended that fishing mortality targets should be set on a precautionary basis so as to minimize the risk of overfishing (e.g. Larkin, 1977; Ludwig *et al.*, 1993; Garcia, 1994; Caddy and Mahon, 1995; Mace, 2001; Punt and Smith, 2001; Punt, 2006). This approach was codified into US law in 1996 and 2006 by revisions to the Magnuson-Stevens Fishery Conservation and Management Act. However, reducing fishing mortality below F_{MSY} will, by definition, result in long-term yields that are less than maximum sustainable yield (MSY). Thus, while precaution gives benefits in that it reduces the risk of overfishing and its concomitant impacts on the marine ecosystem, it also has a cost in that it reduces expected yield (risk is defined here as the probability of an undesirable event) (Francis and Shotton, 1997). The purpose of this paper is to explore these tradeoffs in setting reference points using the Mid-Atlantic sea scallop (*Placopecten magellanicus*) fishery as an example.

Until recently, US sea scallop fishery management used F_{MAX}, the fishing mortality that induces maximal yield-per-recruit, as a proxy for F_{MSY}. Uncertainties in yield-per-recruit analysis can be assessed by estimating a probability distribution for each of the input parameters, repeatedly drawing parameters at random from these distributions and then performing yield-per-recruit analysis using these choices (Restrepo and Fox, 1988). By repeating this procedure a large number of times, the probability distribution of F_{MAX} and the expected yield-per-recruit at a given fishing mortality can be estimated.

Yield-per-recruit reference points are commonly used when stock-recruit relationships are not easily estimable. However, probability distributions for stock-recruit parameters can often be estimated, even if the point estimates are highly uncertain. These distributions can be combined with per-recruit analysis to obtain stochastic yield curves and the probability distributions for the reference points F_{MSY}, MSY, and B_{MSY}. From these, the probability that a given level of fishing F is above the true F_{MSY} (i.e. that overfishing is occurring) as well as the loss in expected yield incurred by fishing at F rather than the true F_{MSY} can be calculated.

Precaution in fishery management is usually implemented by reducing effort or quotas so that the target fishing mortality is reduced below F_{MSY}. Long-term closures of areas to fishing (such as "marine reserves" or "marine protected areas") are another way to implement precaution (Lauck *et al.*, 1998). Here I compare the two approaches by estimating the loss of yield at various levels of precaution by reduction of fishing mortality, or by using area closures.

Besides the uncertainties in the reference points due to parameter uncertainty, the fishing mortality target intended by managers may not be realized precisely due, e.g., to uncertainties in projected biomass and catch, so that the actual fishing mortality may be greater or less than that intended by management. The effects of such implementation uncertainty on reference points will also be considered here.

Methods

Stochastic yield-per-recruit and yield analysis

A description of the basic size-based yield-per-recruit model used in this analysis can be found in the Appendix of Hart (2003). The yield-per-recruit calculations depend on a number of parameters whose estimates are uncertain:

(i) Von Bertalanffy growth parameters K and L_∞

(ii) Shell height/meat weight parameters a and b

(iii) Natural mortality rate M

(iv) Fishery selectivity parameters α and β

(v) The cull size of the catch and the fraction of discards that survive F_D

(vi) The level of incidental fishing mortality i, i.e. non-catch mortality caused by fishing.

In addition, yield calculations require estimates of a stock-recruit function, which was assumed to be of the Beverton-Holt form, requiring two parameters s and γ.

All of these parameters were assigned probability distributions reflecting their level of uncertainty, as discussed below. For each iteration, choices for each of these parameters were drawn from their distributions, and then per-recruit and yield curves were calculated for fishing mortalities between 0 and 1 with a step size of 0.01. This was repeated for $n = 10\,000$ iterations and the results collected. Of particular interest were the expected yield and yield-per-recruit at a given fishing mortality F, and the probability that F is greater than the true F_{MSY}, i.e. that overfishing would be occurring. The expected yield at fishing mortality F was calculated as the mean of the yields at that fishing mortality over all runs, and the stochastic F_{MSY}, with corresponding reference points MSY and B_{MSY}, were calculated as the fishing mortality that maximizes the expected yield curve. Note that this may be different than the mean of the F_{MSY} values over all runs. Other reference points such as F_{MAX} were computed in an analogous manner. The probability that F_{MSY} would be exceeded at a given fishing mortality F was calculated as the number of runs for which the run-specific $F_{MSY} < F$ divided by the total number of runs.

The estimates of four sets of parameters (growth parameters K and L_∞, shell height/meat weight parameters a and b, selectivity parameters α and β and stock-recruit parameters s and γ) are confounded as reflected by a strong correlation between the estimates. For example, a growth curve with a given K and L_∞ resembles one with a slightly smaller K and larger L_∞, implying a negative correlation between the estimates of the two parameters. In these cases, each parameter pair was simulated as correlated normal or chi-squared random variables. In other cases, gamma distributions were used that were assumed to be uncorrelated with the other variables.

Probability distributions for per-recruit parameters

The mean, standard error and correlation (when applicable) for each of the simulated parameters are given in Table 1. Details on each of these parameters are given below.

Growth parameters K and L∞

As discussed above, K and L_∞ were simulated as negatively correlated normals, using the mean and covariance from shell growth increment data, as estimated by a linear mixed-effects model (Hart and Chute, 2009).

Shell height/meat weight relationships

Meat weight W at shell height H is calculated using a formula of the form:

$$W = \exp(a + b\ln(H)) \tag{1}$$

The means, variances, and covariances of parameters a and b were estimated using a generalized linear mixed-effects model (GLMM) based on data collected during the 2001–2008 NEFSC annual sea scallop surveys (Hennen and Hart, 2012). Similar to the growth parameters, the estimates of a and b have a strong negative correlation. This implies that the predicted meat weight at a given shell height carries less uncertainty than it would appear from the variances of the individual parameters.

Natural mortality M

Dead "clapper" scallops (dead scallop shells still attached at the hinge) are an indicator of recent natural mortality due to such causes as disease, high temperatures and sea star predation. The clappers separate some time after death because of hinge degeneration. At equilibrium, the rate of clappers being produced, ML,

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

Parameter	Purpose	Mean	S.E.	Corr.	Distribution
K	Growth	0.508	0.004	−0.6	Corr. Normal
L_∞	Growth (mm)	133.3	0.4	−0.6	Corr. Normal
a	SH/MW	−10.80	0.024	−0.997	Corr. Normal
b	SH/MW	2.97	0.024	−0.997	Corr. Normal
S	Clapper sep. time (y)	33/52	12/52		Gamma
α	Selectivity	15.5	1.95	0.9	Corr. Normal
β	Selectivity	0.139	0.03	0.9	Corr. Normal
F_D	Disc. mort. (y^{-1})	0.2	0.15		Gamma
i	Incid. mort. (y^{-1})	0.1	0.075		Gamma
$\sqrt{s}$	Stock-recruit parameter	279.880	49.150	0.9	Corr. Normal
$\sqrt{\gamma}$	Stock-recruit parameter	0.006 5	0.002 8	0.9	Corr. Normal

where L is the number of live scallops, must equal the rate of loss of clappers C/S, where S is the mean clapper separation time and C is the number of clappers. Solving this for M gives:

$$M = \frac{1}{S}\frac{C}{L} \tag{2}$$

so that natural mortality is proportional to the ratio of clappers to live scallops.

Merrill and Posgay (1964) used this idea to estimate natural mortality for sea scallops on Georges Bank. They estimated a clapper ratio of $C_{GB}/L_{GB} = 0.0662$, and a mean separation time $S_{GB} = 33$ weeks $= 33/52$ years to estimate an annual natural mortality rate of $M_{GB} = (52/33)*0.0662 = 0.104$. Probably the greatest uncertainty in this calculation is the mean separation time S_{GB}. For example, Dickie (1955) estimated the mean clapper separation time to be 100 days (14.3 weeks), less than half that estimated by Merrill and Posgay. Reflecting this uncertainty (as well as other potential uncertainties in this calculation), I assumed S_{GB} was distributed as a gamma random variable, with mean 33 weeks and standard deviation 12 weeks.

No empirical estimate of natural mortality is available for Mid-Atlantic sea scallops. Life history theory suggests that the ratio M/K remains invariant within taxonomic groups (Beverton and Holt, 1959; Jensen, 1996). Assuming this is correct, so that the M/K ratio is the same for both Georges Bank and Mid-Atlantic sea scallops, natural mortality of Mid-Atlantic sea scallops is $M_{MA} = \frac{K_{MA}}{K_{GB}} M_{GB}$. Thus,

$$M_{MA} = \frac{K_{MA} C_{GB}}{K_{GB} S_{GB} L_{GB}} \tag{3}$$

From Hart and Chute (2009), $K_{MA}/K_{GB} = 0.508/0.427 \sim 1.19$. Assuming S_{GB} is distributed as a gamma random variable as discussed above, and neglecting any uncertainty in the other parameters, the resulting distribution of M has the desirable characteristic of being skewed to the right (Figure 1a). This makes sense since, for example, a natural mortality of $M = 0.3$ is possible, but an $M = 0$, or even close to zero, is not. Note that because S_{GB} appears in the denominator of (3), the expected value of natural mortality is not equal to applying equation (3) with the mean value of S_{GB}. For the purposes of comparing the probabilistic calculations with conventional deterministic ones, I used both the median of the natural mortalities (approximately 0.12) and the expected value of natural mortality (approximately 0.15) as point estimates of M.

Fishery selectivity L was estimated using an ascending logistic curve of the form:

$$L = \frac{1}{1 + exp(\alpha - \beta H)} \tag{4}$$

where H is shell height. The means and covariances of the α and β parameters were estimated during 2005–2009 using the CASA stock assessment model (NEFSC, 2010). Note that fishery selectivity reflects targeting as well as gear selectivity.

Discard mortality

Sea scallops that are caught but are < 90 mm are assumed to be discarded, based on at-sea fishery observer data. Sea scallops likely tolerate discarding fairly well, provided they are returned to the water relatively promptly and they are not damaged by the capture process or their time on deck. Here, discard mortality was simulated as a gamma distribution, with a mean of 0.2 and a standard deviation of 0.15, reflecting the high uncertainty in this parameter.

Incidental fishing mortality

Incidental fishing mortality occurs when scallops are killed but not captured by the gear. Let F_L be the fully recruited landed fishing mortality rate and F_I be the rate of incidental fishing mortality. F_I should be proportional to F_L, say $F_I = i\ F_L$. Based on the studies of Caddy (1973) and Murawski and Serchuk (1989), i was

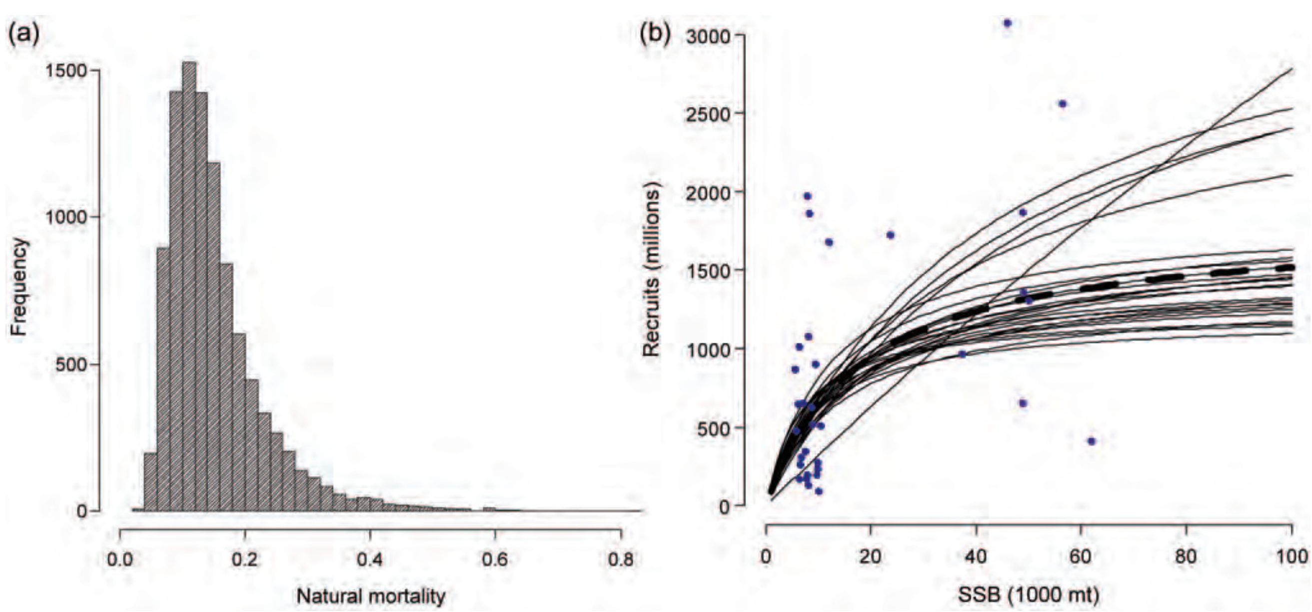

Figure 1. (a) Distribution of the natural mortality parameter M. (b) Stock-recruit data (solid circles), together the estimated median stock-recruit curve (thick dashed line), and 25 example stock-recruit curves (thin solid lines) from the Monte-Carlo simulations.

estimated as a gamma distribution with a mean of 0.1 and standard deviation of 0.075.

Estimating stock-recruit relationships and yield curves

A Beverton-Holt stock-recruitment relationship was assumed to be of the form:

$$R = \frac{sB}{1 + \gamma B}, \tag{5}$$

where R is recruitment, and B is spawning stock biomass (or egg production). The parameters s and γ were estimated for Mid-Atlantic sea scallops from stock biomass and recruitment estimated by the CASA stock assessment model (NEFSC, 2010) from 1977–2009, assuming square root normal (chi-squared) errors in recruitment (Figure 1b). Sea scallops become sexually mature at age two (MacDonald and Thompson, 1985); CASA biomass estimates are for individuals > 40 mm shell height, which are two years old or greater, so that the entire biomass in these estimates consist of mature scallops. The two stock recruit parameters were modelled as correlated square-root normal distributions, with means and covariances as estimated from stock assessment model data.

Equilibrium recruitment at fishing mortality F is given by

$$R = \frac{sb - 1}{\gamma b} = \frac{1}{\gamma}(s - 1/b) \tag{6}$$

where b is spawning stock biomass (or egg) per recruit. Yield is therefore

$$Y = yR = \frac{y}{\gamma}(s - 1/b) \tag{7}$$

where y is yield-per-recruit.

The above calculations assume all areas are open to fishing. If instead a fraction C of the recruitment occurs in areas closed to fishing long-term, under the assumptions that adults do not move between the fished and closed areas but larvae are well-mixed, equation (7) is replaced with (Hart, 2006):

$$Y(F, C) = \frac{(1 - C)y}{\gamma}\left[s - \frac{1}{(1 - C)b + Cb(0)}\right]. \tag{8}$$

Fishing mortality F is defined here as the rate of removals outside the closures, rather than whole-stock fishing mortality, so that fishing mortality does not explicitly depend on the closure fraction.

Sea scallops are highly fecund with a low probability of stock collapse due to recruitment failure. In order to evaluate how the results would change for a more vulnerable stock, the model was also run with the values of the stock recruitment parameters s and γ divided by two compared to those estimated for sea scallops. This had the effect of reducing the slope of the stock recruit curve at the origin by two while leaving the asymptotic recruitment level unchanged, thereby making recruitment failure much more likely. The model runs using the estimated stock recruit parameters for Mid-Atlantic sea scallops will be referred to as the standard or baseline case, whereas the runs where the stock recruit parameters were halved will be termed the low steepness case.

The mean and median stochastic yield curves were calculated as the mean and median of the yield curves for the 10 000 runs. A trimmed mean was also calculated as the mean of the runs after the highest and lowest 10% of the runs were removed. The simulations were implemented in R (version 2.12.1) which called a Fortran-90 subroutine that performed the yield-per-recruit calculations.

Incorporating implementation (management) uncertainty

The actual fishing mortality realized may be different from the target fishing mortality set by managers due, e.g., to uncertainty in biomass or catch (Chen and Wilson, 2002; Ralston *et al.*, 2011). Thus, for a fixed target fishing mortality F_{TARGET}, the actual fishing mortality F_a is a random variable with density function $p(F)$. We denote by $y(F)$ the expected yield obtained by fishing at F, and $y_t(F)$ the expected yield obtained by setting the target fishing mortality at F. Note that these will be different, even if the process of setting the management targets is unbiased, because yield-per-recruit and yield curves are non-linear. The expected yield obtained from setting the target at F_{TARGET} is:

$$y_t(F_{TARGET}) = \int_0^\infty p(F)y(F)\,dF. \tag{9}$$

For these analyses, I assumed that the density function $p(F)$ is normal (in principle, this needs to be truncated at 0, but in practice there is negligible probability that $F < 0$) with its mean and standard deviation denoted by F_{TARGET} and σ, respectively. The integral was estimated numerically with a step size of 0.01. Two levels of management uncertainty were considered, representing moderate to high uncertainty: $\sigma = 0.05$ and 0.1.

Results

Yield-per-recruit and yield curves were highly variable among runs (Figure 2), which induced substantial uncertainty in these reference points (Figure 3). The yield-per-recruit reference point F_{MAX} was highly variable, with the estimate hitting the boundary value of $F_{MAX} = 1$ over 7% of the time. This variation was reduced in the estimates of F_{MSY} for the baseline case because high fishing mortality can reduce recruitment even when it optimizes yield-per-recruit. Low steepness induced high variability in the estimates for MSY and B_{MSY}; most estimates were lower than in the baseline case, but a small percentage of the runs gave very high estimates.

The stochastic median yield curve in the baseline case, as well as the median stochastic yield-per-recruit curve, lie between the corresponding deterministic curves that assume $M = 0.12$ (the median estimate of M) and $M = 0.15$ (the expected value of M) (Figure 4). However, in the low steepness case, the median stochastic yield curve is below both deterministic curves. This is due to a substantial proportion of runs where little or no yield is produced beyond a critical fishing mortality level because of stock collapse. This does not affect the deterministic curves until they predict collapse between $F = 0.6$ and $F = 0.7$, but does reduce the estimates of the stochastic curves. Stock collapse occurred about 11% of the time, even at no fishing, assuming low steepness; this percentage increased with fishing mortality and was $> 50\%$ for $F > 0.7$.

Mean and, to a lesser extent, trimmed mean stochastic yield-per-recruit curves were greater than the median curve,

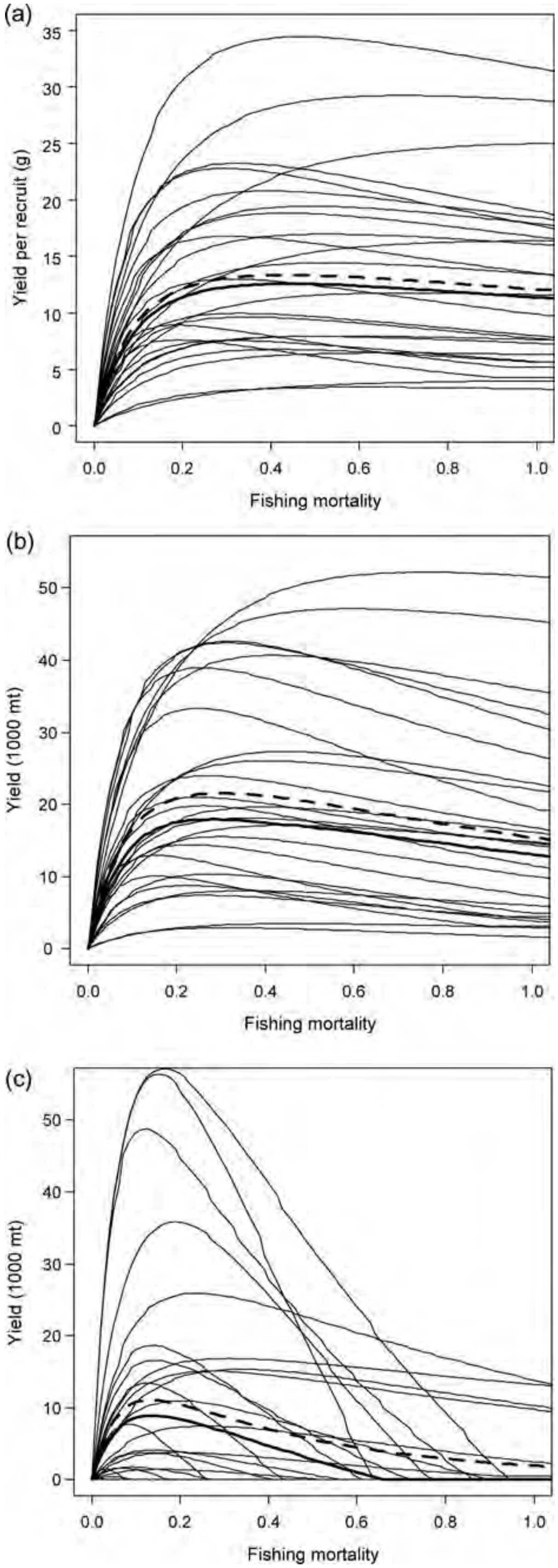

Figure 2. Median (thick solid line) and trimmed mean (dashed line) (a) yield-per-recruit curves, (b) yield curves, and (c) yield curves with low steepness. Twenty-five example curves from the Monte-Carlo simulations (thin lines) are also shown.

primarily due to the skewed distribution of natural mortality. The stochastic mean yield and biomass curves were much greater than the median ones, especially at lower fishing mortalities, because they were influenced by a small fraction of runs with very high yields. The stochastic yield curves tend to decline faster than the deterministic ones as fishing mortality increases in the baseline case. This is due to a small probability of very low or zero yields at higher fishing mortalities affecting the stochastic estimates of yield but not the deterministic estimates. Mean and trimmed mean yield estimates remain positive at high fishing mortalities in the low steepness case because of a minority of runs where collapse did not occur. Stochastic fishing mortality reference points (F_{MAX} and F_{MSY}) were somewhat less than the deterministic ones (Table 2).

The tradeoffs between yield and the risks of overfishing and stock collapse are shown in Figure 5. The loss in yield incurred by reducing fishing mortality near F_{MSY} is small because the slope of the expected loss curve is almost zero. On the other hand the slope of the probability of overfishing curve, and in the low steepness case, the slope of the probability of stock collapse curve, are close to their maximum values near F_{MSY}. Thus, reducing fishing mortality near F_{MSY} produces considerable benefits (in terms of reduced risk of overfishing and possibly stock collapse) at only a small cost (reduced expected yield). However, as fishing mortality is further decreased, yield is lost at an increasing rate, whereas the risk curves for overfishing and stock collapse become flatter. Thus, the benefits from reducing fishing mortality become less and costs increase. These tradeoffs are more critical in the low steepness case, where there is a greater need for precaution because of the more substantial probability of stock collapse. However, near optimal yields were achieved in a narrower range of fishing mortalities than in the baseline case, so that the cost of precaution will also be higher.

Implementation error tended to reduce expected yield for fishing mortalities near F_{MSY}, but made little difference on average for higher fishing mortalities where the yield curves are almost linear (Figure 6a and b). Implementation error increased the risk of overfishing at lower fishing mortalities but decreased it at higher fishing mortalities (Figure 6c and d). Implementation error did not appreciably affect the risk of stock collapse since this risk is a nearly linear function of fishing mortality. Target fishing mortality reference points, which take into account that the realized fishing mortality may be different than that targeted, tended to be slightly higher than those that ignore implementation error, whereas implementation error lowered yield and biomass reference points (Table 2).

Long-term fishery closures (marine protected areas or marine reserves) tend to reduce yield at low fishing mortalities but may increase them at fishing mortalities $> F_{MSY}$ especially in the low steepness case (Figure 7a and b). Closing areas to fishing can considerably reduce the risk of stock collapse at a fixed fishing mortality rate (Figure 7c and d). Closures reduce *MSY* while increasing F_{MSY} and B_{MSY} (Table 2).

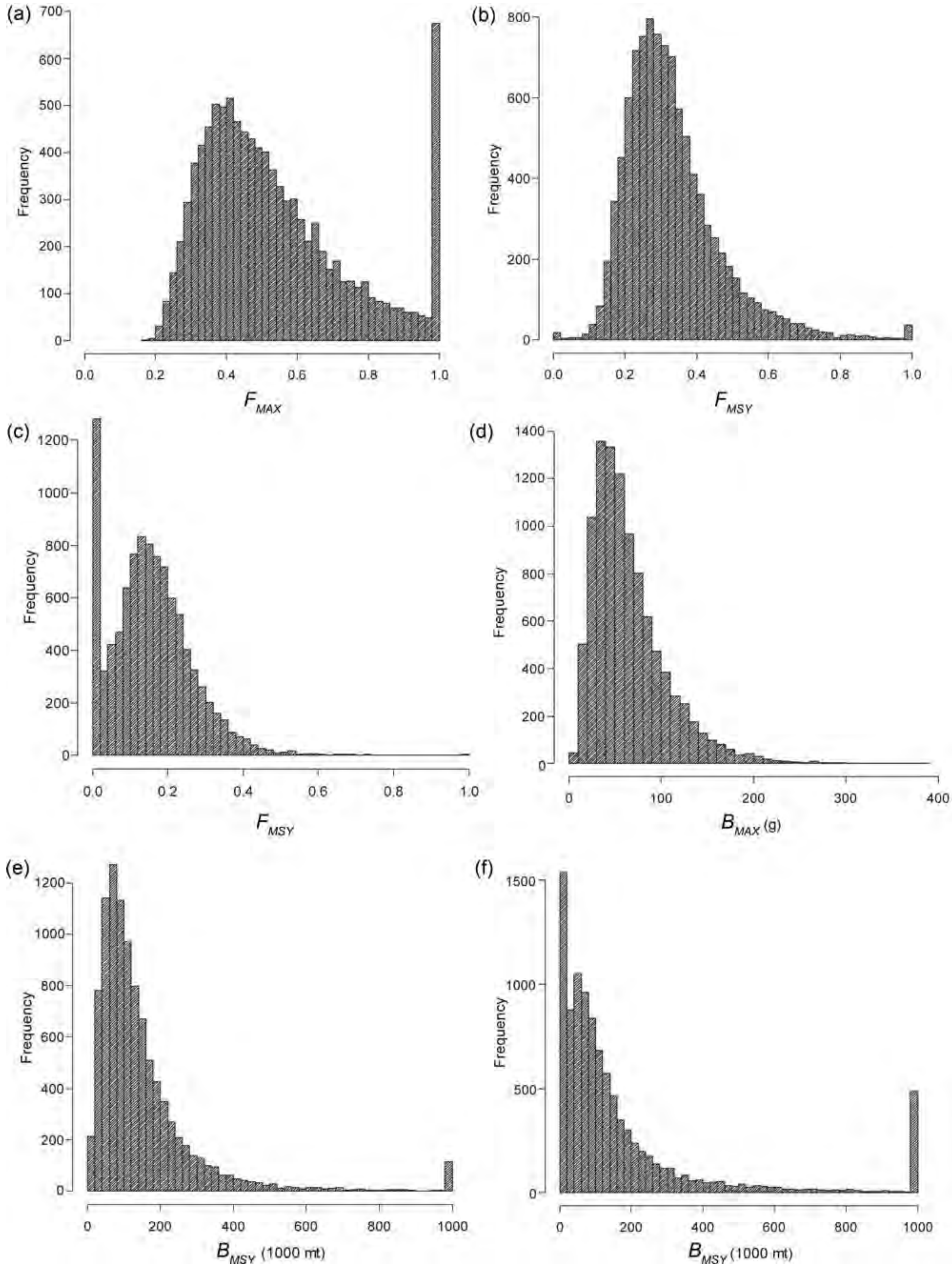

Figure 3. Distributions of estimates of (a) F_{MAX}, (b) F_{MSY} for baseline case, (c) F_{MSY} assuming low steepness, (d) Y_{MAX}, (e) MSY for baseline case, (f) MSY assuming low steepness, (g) B_{MAX}, (h) B_{MSY} for baseline case, and (i) B_{MSY} assuming low steepness, from 10 000 Monte-Carlo simulations.

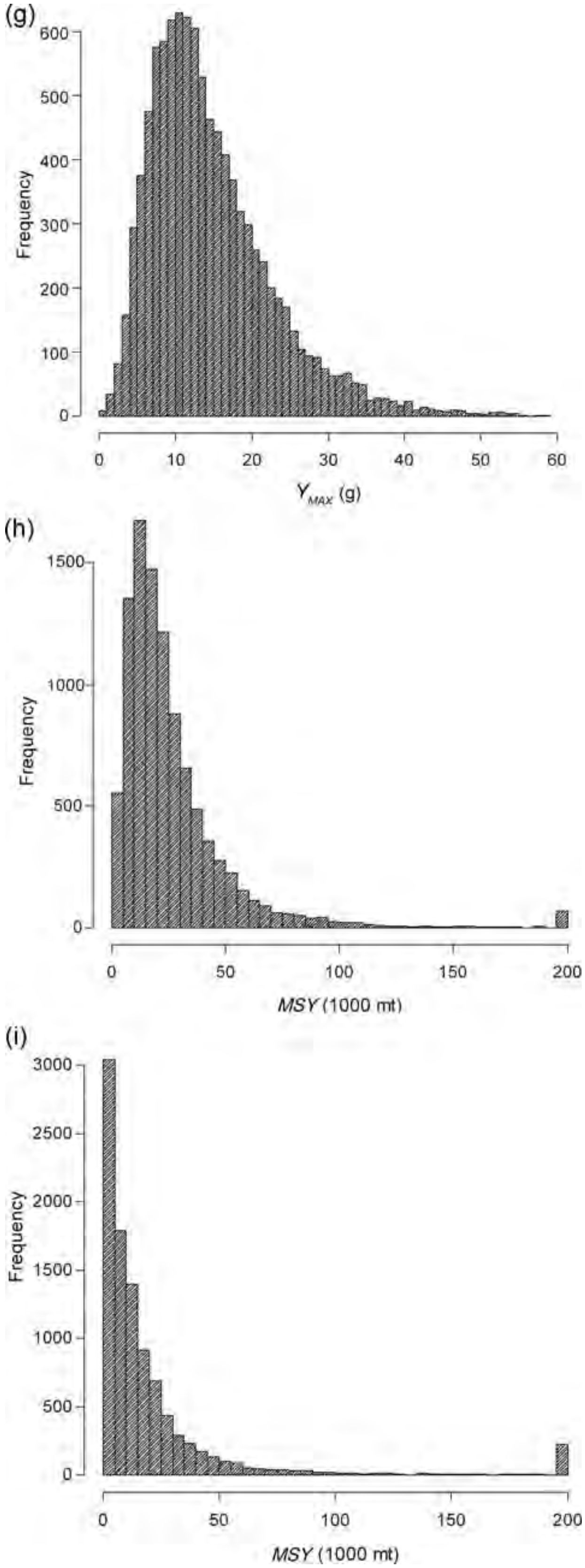

Figure 3 Continued

The risk of stock collapse can be reduced by either reducing fishing mortality or by implementing a fishery closure. Both alternatives will reduce yield for fishing mortalities $< F_{MSY}$. Reducing fishing mortality decreases yield less than implementing long-term closures at the same risk of stock collapse (Figure 7e and f). Thus, precaution in the form of reduced fishing mortality has less "cost" in terms of lost yield than closing an area when they have the same benefit in terms of lowered risk of collapse.

Discussion

The methods presented here take into account the uncertainties in parameters and management implementation that are ubiquitous in practical implementations of reference points. These methods are quite general, and only require estimates of uncertainty for the input parameters to the per-recruit and stock-recruit calculations. For example, it would be straightforward to apply these ideas if the per-recruit calculations are age-based (rather than the length-based ones used for sea scallops) by including the uncertainty in weight-at-age estimates.

Mean stochastic yield curves, computed as the mean of the predicted yields from the stochastic runs, were often unrealistically high due to a small fraction of runs (typically $< 1\%$) that gave extreme results. The stock-recruit parameters in these exceptional runs imply that biomass levels well beyond that observed would produce much higher mean recruitment than that seen in the time-series. While such a possibility cannot be completely ruled out, the extreme yields obtained in these runs tend to dominate the mean, even though they occurred in only a few of the 10 000 simulations. Similarly, a small proportion of the runs unrealistically predict stock collapse even at low or zero fishing mortality. For these reasons, a trimmed mean or the median are preferable measures of central tendency for computing stochastic yield curves.

Stochastic estimates of F_{MSY} were lower than deterministic estimates because only the stochastic reference points take into account the risk that F_{MSY} has been overestimated due to parameter misestimation. Specifically, fishing at the deterministic F_{MSY} estimates have a probability of > 0.5 of overfishing (i.e. of being over the true F_{MSY}) in both the baseline and low steepness cases, whereas the probability of overfishing at all the stochastic estimates of F_{MSY} (mean, median, and trimmed mean in both the baseline and low steepness runs) is < 0.5.

While it has often been recommended that fishing mortality targets should be set below the deterministic F_{MSY} because of such uncertainties, the approach presented here gives a way of quantifying both risks due to parameter uncertainty and the cost of precaution in terms of forgone yield. For example, in the baseline case, fishing at $F = 0.24$ would incur a risk of inducing overfishing of ~ 0.25 while costing about 1% (using either the median or trimmed mean yield curves) of the yield that could be obtained by fishing at the stochastic median or trimmed mean F_{MSY}. Further precaution would come at higher cost. For example, fishing at $F = 0.20$ would reduce the risk of overfishing to less than 0.12, but would induce an expected loss of yield of over 3%. Both the risks and costs are greater in the low steepness case. For example, fishing at $F = 0.075$ would carry about a 25% chance of overfishing while reducing the median or trimmed mean yields by about 11% compared to the corresponding estimated stochastic MSY levels; it also reduces the risk of collapse

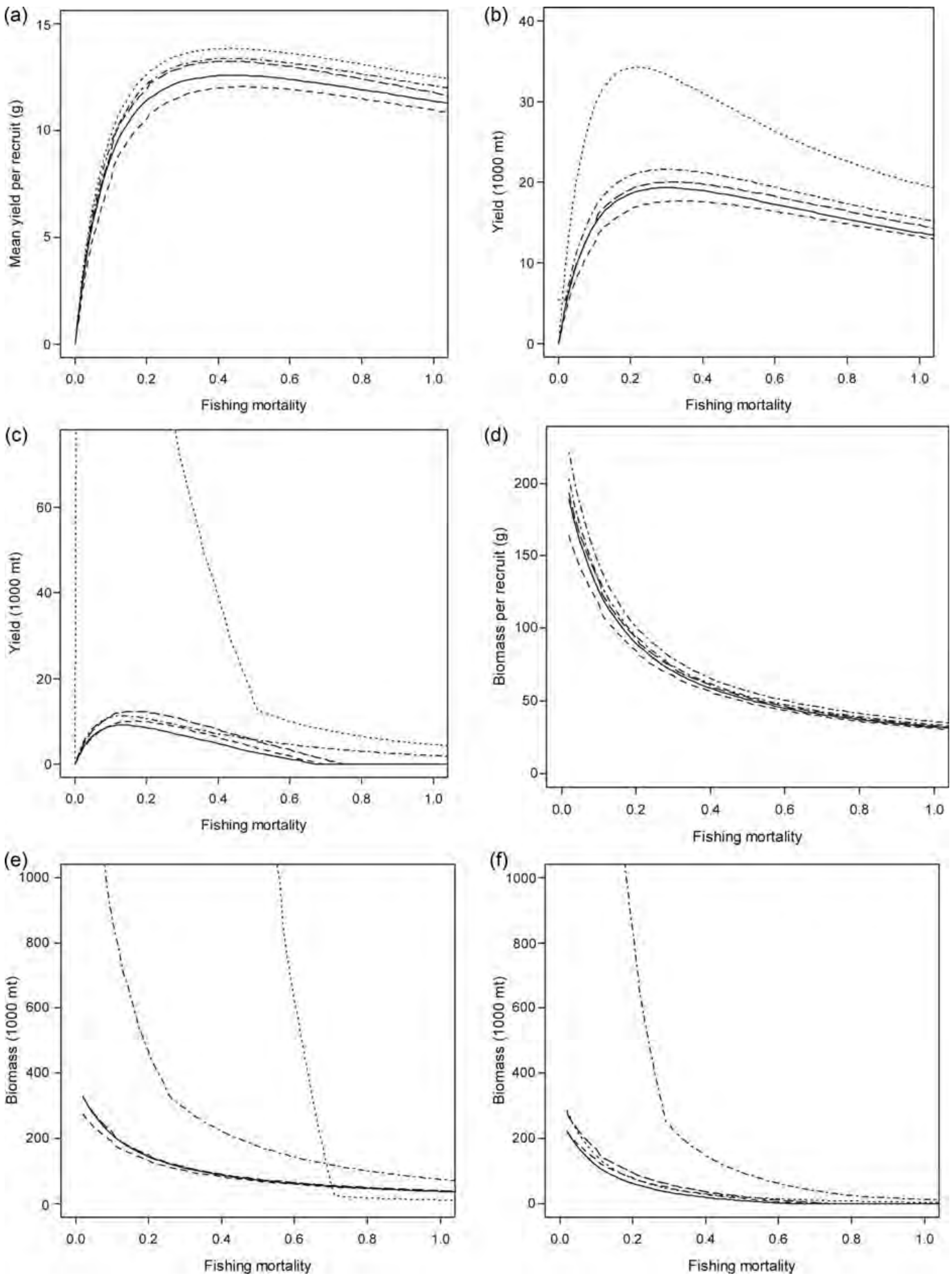

Figure 4. Comparison of stochastic mean (dotted line), trimmed mean (dashed-dotted line) and median (solid line) for (a) yield-per-recruit, (b) yield, (c) yield assuming low steepness (solid lines), (d) biomass per recruit, (e) biomass, and (f) biomass assuming low steepness, to corresponding deterministic curves. Short dashes indicate the deterministic curves with the median natural mortality $M = 0.12$, whereas long dashes give the deterministic curves assuming the mean natural mortality $M = 0.15$.

Table 2. Estimates of the reference points F_{MAX}, F_{MSY}, MSY, B_{MAX}, and B_{MSY}, calculated under various assumptions.

	F_{MAX}	F_{MSY}	Y_{MAX}	MSY	B_{MAX}	B_{MSY}
			Baseline case			
Deterministic, $M = 0.15$	0.49	0.33	11.6	16 827	48.9	93 341
Deterministic, $M = 0.12$	0.46	0.32	12.4	18 448	50.1	106 739
Stochastic, mean	0.43	0.17	14.2	94 003	62.3	1 283 566
Stochastic, median	0.43	0.29	12.5	19 189	55.5	112 130
Stochastic, tr. mean	0.43	0.30	13.2	21 491	58.5	121 685
Stoch. tr. mean w/5% impl err	0.45	0.31	13.2	21 101	57.4	119 792
Stoch. tr. mean w/10% impl err	0.47	0.34	13.1	20 809	56.5	115 145
Stoch. tr. mean w/10% closure	0.43	0.34	11.9	20 133	60.8	143 039
Stoch. tr. mean w/40% closure	0.43	0.40	7.9	14 177	96.6	227 654
			Low steepness case			
Deterministic, $M = 0.15$	0.49	0.17	11.6	10 064	48.9	92 172
Deterministic, $M = 0.12$	0.46	0.17	12.4	12 365	50.1	110 394
Stochastic, mean	0.43	0.06	14.2	5 462 517	62.5	125 905 403
Stochastic, median	0.43	0.14	12.5	8 840	55.5	95 131
Stochastic, tr. mean	0.43	0.13	13.2	11 060	57.8	123 684
Stoch. tr. mean w/5% impl err	0.45	0.16	13.2	10 469	57.4	110 133
Stoch. tr. mean w/10% impl err	0.47	0.21	13.1	9 517	56.5	99 703
Stoch. tr. mean w/10% closure	0.43	0.15	11.9	10 582	60.8	128 667
Stoch. tr. mean w/40% closure	0.43	0.26	7.9	8 544	96.6	156 698

Deterministic calculations use either $M = 0.12$ (the median stochastic estimate of M) or $M = 0.15$ (the expected value of M). Stochastic estimates were based on yield-per-recruit and yield curves constructed by taking either the mean, median, or 10% trimmed mean of the runs. The trimmed mean estimates were also calculated using implementation error or long-term closures.

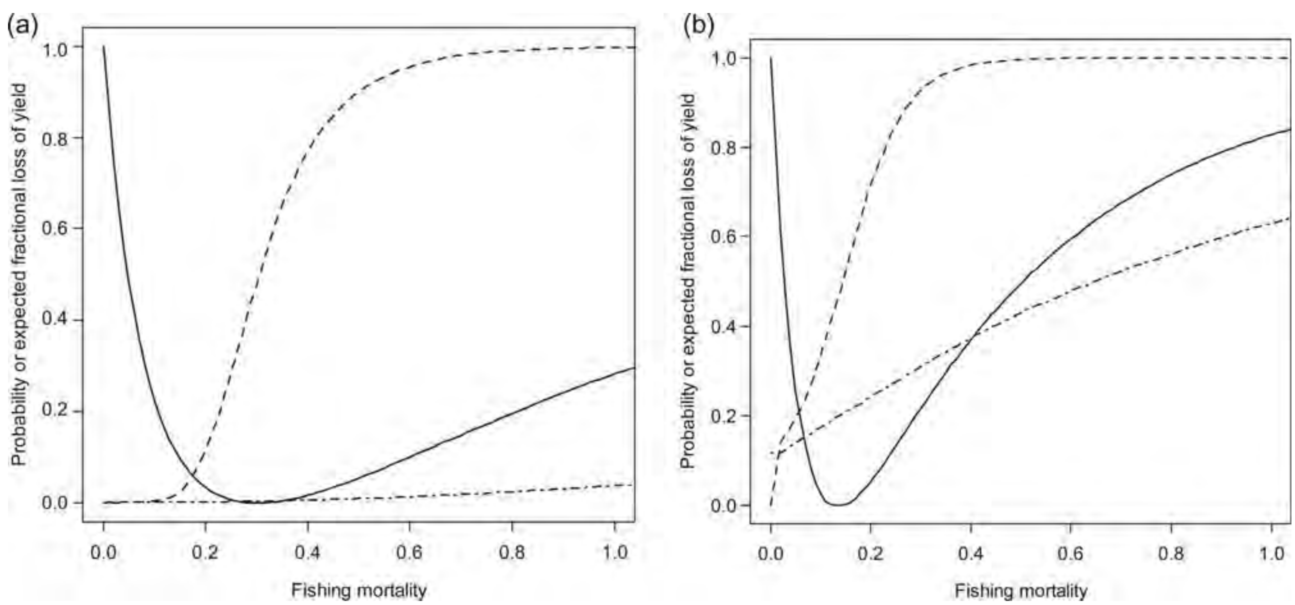

Figure 5. Expected loss of yield (solid line), probability of overfishing (dashed line), and probability of collapse (dashed-dotted line) assuming (a) the standard stock recruit parameters, and (b) low steepness.

by about 5%. Such calculations could be presented to managers to allow them to make an informed decision regarding the appropriate level of risk they are willing to take.

Both fishery closed areas ("marine protected areas") and reducing fishing mortality below F_{MSY} can be part of a precautionary approach to fisheries management in that both can reduce the probability of stock collapse, albeit at a cost of reduced yield. The analysis presented here suggests that reducing fishing mortality, when practical, will lower the risk of stock collapse more at the same "cost" in terms of forgone yield than implenting a closure. Thus, reductions in fishing mortality may often be a better way of implementing precaution than closures. Closures may still be a more practical strategy in areas which lack the scientific and management infrastructure necessary to estimate and control fishing mortality. They can also be useful as reference areas and for habitat protection.

Implementation uncertainty will always reduce expected yield for fishing mortalities near F_{MSY}. This is because the yield curve is concave near its maximum, so that the mean of the yields over a range of fishing mortalities near F_{MSY} will be less than the yield at the mean of these fishing mortalities by Jensen's inequality (Feller, 1966; Hart, 2001). At fishing mortalities much higher or

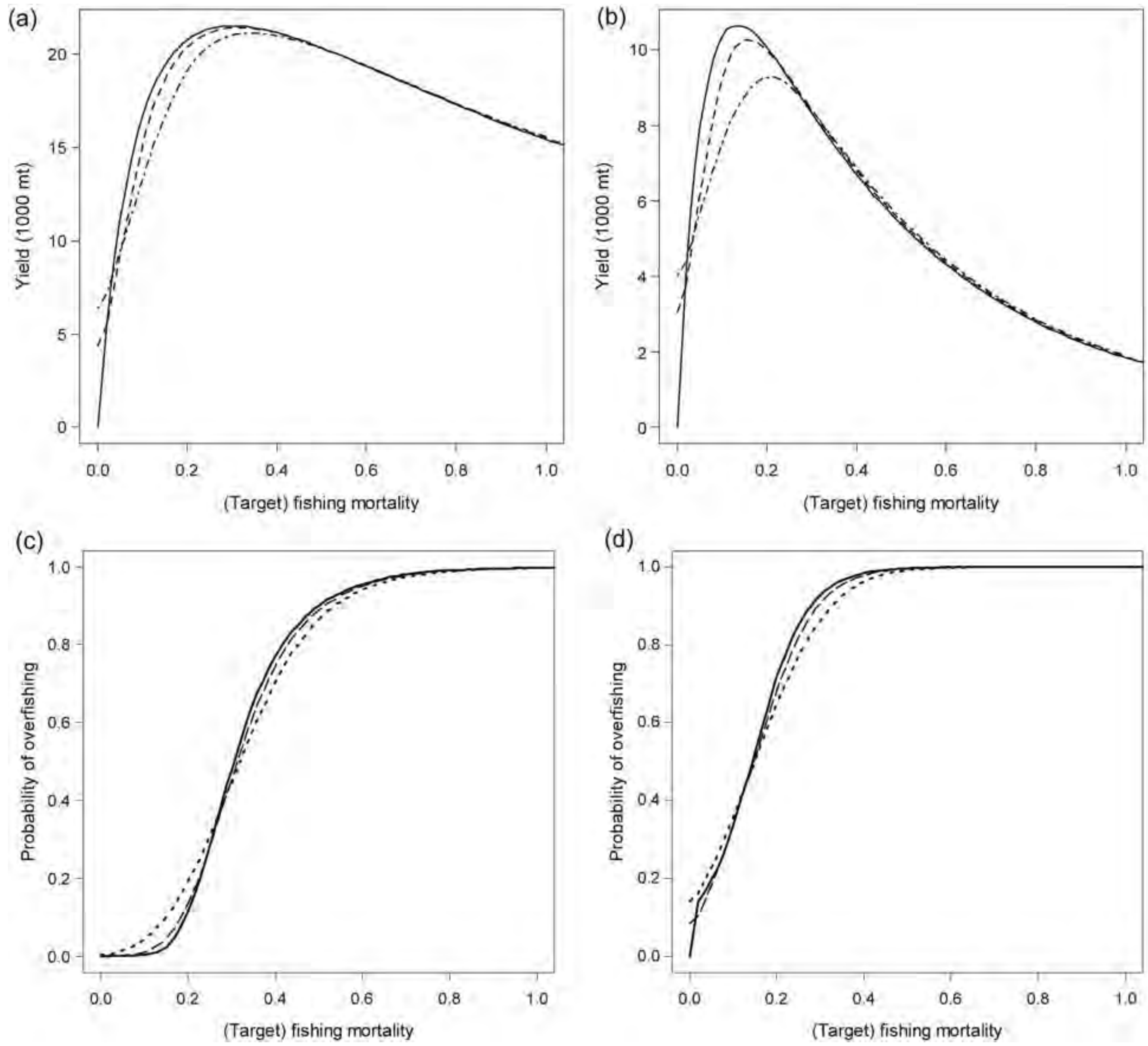

Figure 6. Effects of implementation error on yield [(a) standard case, (b) low steepness case] and the probability of overfishing [(c) standard case, (d) low steepness case]. For each graph, implementation error was assumed to be 0 for the solid lines, 5% for the dashed lines, and 10% for the dashed-dotted lines.

lower than F_{MSY}, the loss of expected yield due to implementation uncertainty will be less because the yield curve is almost linear. Similarly, the expected biomass at a given targeted fishing mortality will be greater if implementation error is included because biomass curves are convex functions of F. In the cases examined here, the fishing mortality targets that optimized yield (taking into account implementation uncertainty) were higher than those calculated without implementation error. This is due to the asymmetry of the yield curves, which drop faster as fishing mortality is reduced below F_{MSY} than when it increases above F_{MSY}. Thus, more yield is lost by fishing below F_{MSY} by a given amount than fishing above by that amount, so it is optimal to increase the target fishing mortality to slightly above the F_{MSY} estimated without error in order to reduce the chance of underfishing.

An alternative way to compute stochastic reference points would be to take the mean (or median or trimmed mean) of the reference points computed from each run. However, such an approach can produce inconsistent results. For example, it may not be true that fishing at the mean of F_{MSY} over all runs would produce the same expected yield as the mean of MSY over all runs, nor would it necessarily produce the greatest expected yield. This can particularly be problematic when the distribution of F_{MSY} is skewed to the right, so that fishing at the mean of the F_{MSY} values would have a probability of overfishing > 0.5.

It is possible that some of the parameters assumed to be independent are in fact correllated. For example, life history theory suggests that the natural mortality rate M should be correlated with the Brody growth coefficient K among similar stocks (Beverton and Holt, 1959; Jensen, 1996). In some cases, therefore, it would be better to model M and K as correlated variables, similar to the way L_∞ and K were modelled. For Mid-Atlantic sea scallops, K has been precisely estimated (Hart and Chute, 2009) whereas M is highly uncertain. Thus, there is likely to be little or no correlation between the probability distribution for the uncertainty in K with that of M in this particular case.

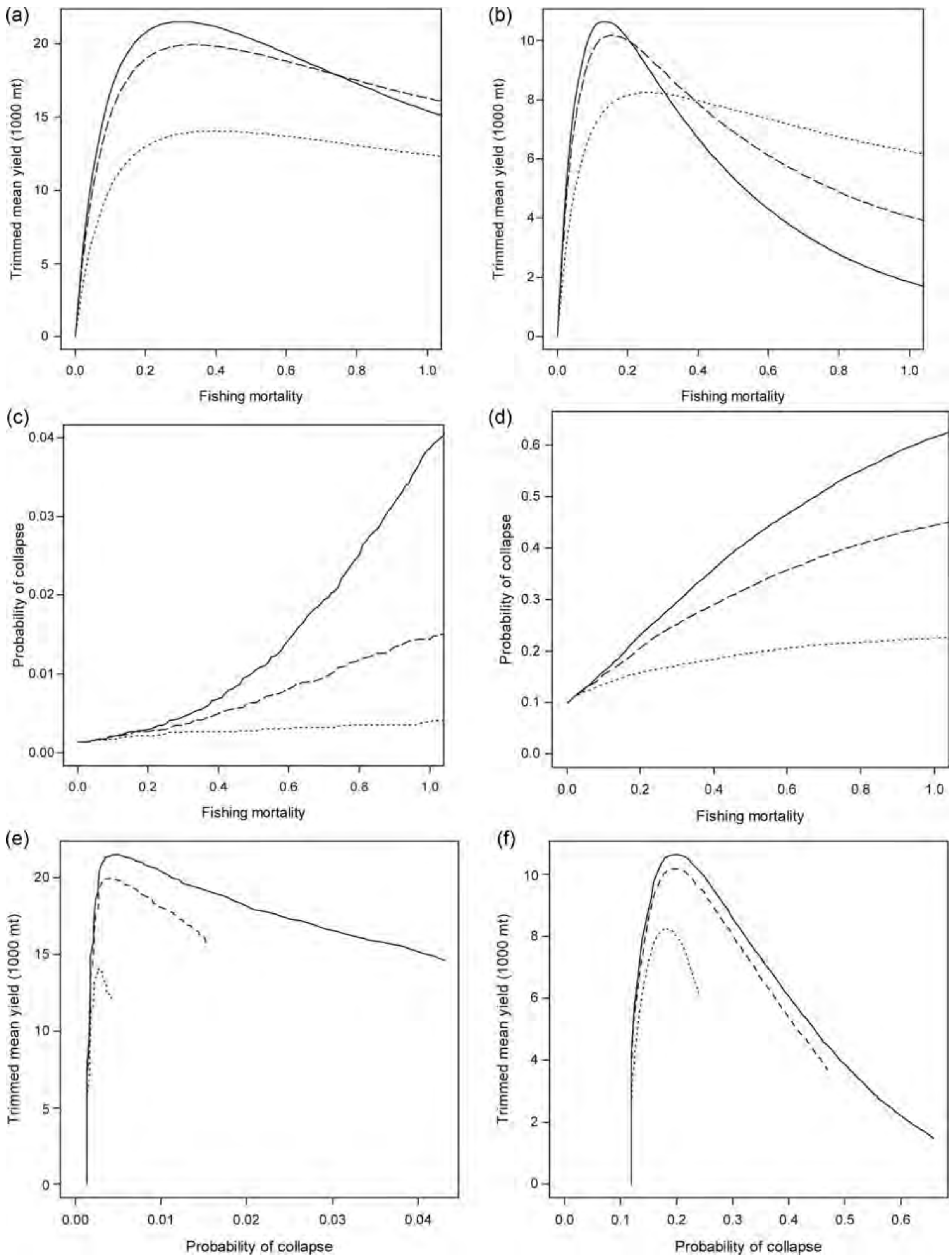

Figure 7. Effects of fishery closures (solid line is no closure, dashed line represents 10% closure, and the dotted line represents 40% closure) on yield and the probability of collapse. Trimmed mean yield as a function of fishing mortality for the standard parameters is given in (a) and for the low steepness case in (b). The probability of collapse for the standard and low steepness cases are given in (c) and (d), respectively. Trimmed mean yield as a function of the probability of collapse are show in (e) for the standard case and (f) for the low steepness case.

This article focuses on the effects of parameter and implementation uncertainty on reference points. It neglects model error, where the true processes are different from those modelled. Model error is very difficult to quantify, but the possibility of model error implies that the calculated uncertainties may be underestimated. Non-parametric models that are based on fewer assumptions than conventional parametric models may be a way of reducing or at least evaluating model error (Cadigan, 2013). Process error in which, e.g., recruitment and natural mortality may vary temporally, was also not explicitly considered. Long frequency variations in parameter values due, e.g., to regime shifts or changes in predation levels, could substantially change reference points (Jacobson and MacCall, 1995; Collie and Gislason, 2001). The methods used here to assess the effects of misestimation of parameters could also be similarly used to evaluate the effects of potential long-term changes to parameter values.

Equilibrium analyses, such as that presented here, have the advantage of simplicity and can best be used for strategic guidance. However, this type of analysis cannot evaluate, e.g., the impact of misestimated fishing mortality or parameters on rebuilding plans, nor can it directly assess the risks of short-term recruitment failure or catastrophes. These issues need to be evaluated by dynamic simulations, often characterized as "management strategy evaluations" (see e.g. Francis, 1993; Megrey *et al.*, 1994; Butterworth and Punt, 1999; Fieberg, 2004; Kell *et al.*, 2005; McGillard *et al.*, 2011; Collie *et al.*, 2012; Punt *et al.* 2012).

The methods presented here represent a first step towards a full cost-benefit analysis for precautionary management of fisheries. While it presents quantitative tradeoffs between the risks of overfishing and stock collapse on one hand, and the loss of expected yield due to precaution on the other, these quantities are not in comparable units. Although the loss of yield from precautionary practices can be readily translated into economic losses, it is more difficult, and beyond the scope of the present work, to assign social-economic costs to the risks of overfishing and stock collapse. A number of methods are available to attempt to quantify these costs (e.g. Ludwig, 2002; Sethi, 2010; Sethi *et al.*, 2012).

It has become widely accepted that target fishing mortality rates should be set precautionarily below F_{MSY} in order to account for uncertainty (e.g. Larkin, 1977; Garcia, 1994; Caddy and Mahon, 1995; Francis and Shotton, 1997; Mace, 2001; Punt and Smith, 2001; Punt, 2006). Early implementations of this idea tended to be *ad hoc*, where fishing mortality targets were set at some fraction of F_{MSY}. However, there has been increasing interest in more quantitative precautionary methodologies (Thompson, 1992; Caddy and McGarvey, 1996; Prager *et al.*, 2003; Shertzer *et al.*, 2008; Ralston *et al.*, 2011). Typically, the target fishing mortality rate is set so that the risk of overfishing is less than some probability $p^* < 0.5$ While some management judgement as to the value of p^* to use is still required, this method allows managers to make a more informed choice of risks than *ad hoc* reductions in F or quota.

Most of these previous studies separate uncertainty into scientific uncertainty, including both uncertainty in estimated and projected biomass as well as in the reference point calculations, and management uncertainty of the projected catch targets and limits. A slightly different approach is taken here, where uncertainty in the reference point calculations alone are evalutated, whereas what is termed here as "implementation uncertainty" includes both uncertainty in projected biomass estimates as well as management uncertainty. While both approaches would be similar in practice, it is of interest to understand the contribution of reference points alone to uncertainty, rather than have this quantity lumped in with uncertainty in projected biomass.

This paper builds on previous works and makes several advancements. First, it calculates the tradeoff between precaution and lost yield, allowing managers to make a more informed decision as to the desired level of risk. Second, it considers two different types of risk: the risk of overfishing at a given target fishing mortality, and the risk of stock collapse. For resilient stocks such as sea scallops, there is unlikely to be any serious consequences of fishing modestly greater than F_{MSY}; it would only slightly reduce long-term yield. For less sturdy stocks, however, fishing over or even somewhat below the mean estimated F_{MSY} may induce a more serious risk of stock collapse. While it has been generally understood that less resilient, low steepness stocks require more precaution, the approach here demonstrates how this intuition can be put on a more quantitative and rigorous basis. Finally, the methods presented here directly integrate parameter uncertainty into both the risk and yield calculations. While several authors have estimated the uncertainty of per-recruit calculations by propagating parameter uncertainty (e.g. Restrepo and Fox, 1988; Restrepo *et al.*, 1992; Grabowski and Chen, 2004; Jiao *et al.*, 2005; Chang *et al.*, 2009), this paper demonstrates how this type of analysis can be combined with uncertainty of stock-recruit parameters and management implementation for determining reference points.

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