A probability-based approach to setting annual catch levels

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Abstract—The requirement of setting annual catch limits to prevent overfishing has been added to the Magnuson–Stevens Fishery Conservation and Management Reauthorization Act of 2006 (MSRA). Because this requirement is new, a body of applied scientific practice for deriving annual catch limits and accompanying targets does not yet exist. This article demonstrates an approach to setting levels of catch that is intended to keep the probability of future overfishing at a preset low level. The proposed framework is based on stochastic projection with uncertainty in population dynamics. The framework extends common projection methodology by including uncertainty in the limit reference point and in management implementation, and by making explicit the risk of overfishing that managers consider acceptable. The approach is illustrated with application to gag (*Mycteroperca microlepis*), a grouper that inhabits the waters off the southeastern United States. Although devised to satisfy new legislation of the MSRA, the framework has potential application to any fishery where the management goal is to limit the risk of overfishing by controlling catch.

Manuscript submittted 28 September 2007.
Manuscript accepted 15 February 2008.
Fish. Bull. 106:225–232 (2008).

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The Magnuson–Stevens Fishery Conservation and Management Reauthorization Act of 2006 (MSRA) requires that each Fishery Management Plan in the United States "establish a mechanism for specifying annual catch limits ... at a level such that overfishing does not occur in the fishery ..." (MSRA, 2006). This requirement, which reflects an increased emphasis on conservation, is new in the sense that prevention of overfishing is mandated to be through annual catch limits (ACLs), rather than only through such less restrictive measures as trip limits, size limits, or days allowed at sea. Because the statute requires ACLs to be implemented by 2011 in all fisheries (by 2010 for fisheries where overfishing is occurring), discussion has begun on ways to compute them. Accompanying the discussion of ACLs is the discussion of corresponding annual catch targets (ACTs), levels of catch set as quotas in the fishery.

In this study, we propose a method for setting annual catch levels that are treated as targets, but equally well could serve as limits. The method is based on stochastic projection with uncertainty in population dynamics. It extends usual projection methodology by including uncertainty in the limit reference point and in management implementation, and by making explicit the overfishing risk that managers consider acceptable. This probabilistic approach was devised specifically to satisfy the U.S. statute, but we expect it should be useful whenever the management approach is to limit the risk of overfishing by controlling catch.

From a technical point of view, the requirement to set ACLs is interesting in that overfishing is defined in terms of a fishery input (i.e., fishing-induced mortality rate), yet the control mechanism is defined in terms of a fishery output (i.e., catch). (Review of inputs and outputs in fishery management can be found in Morison [2004] and Walters and Martell [2004].) Values connecting inputs and outputs mathematically are stock abundance and age structure, which change from year to year. Ideally, then, a method to set catch levels would take into account both uncertainty in the estimates of current stock abundance and structure and the expectation that abundance and structure will change with time. Current harvest-control rules for fisheries usually depend on a limit reference point, and uncertainty in estimating the limit reference point should also be considered. The limit reference point (typically the fishing rate at maximum sustainable yield (F_{MSY}) or a proxy for it) is generally considered to represent the level at which overfishing occurs (Mace, 2001).

Given the uncertainties in population dynamics, stock assessment, and fishery management, it is arguably impossible to fish without some risk of overfishing. Rather than attempting to achieve zero probability of overfishing, our approach avoids overfishing in a probabilistic sense by keeping the expectation of overfishing below a preset level (e.g., 0.1), presumably satisfying the new requirement of the MSRA. The approach is intended for setting annual catch levels while accommodating uncertainties in future stock dynamics, assessment results, and in the implementation of management measures.

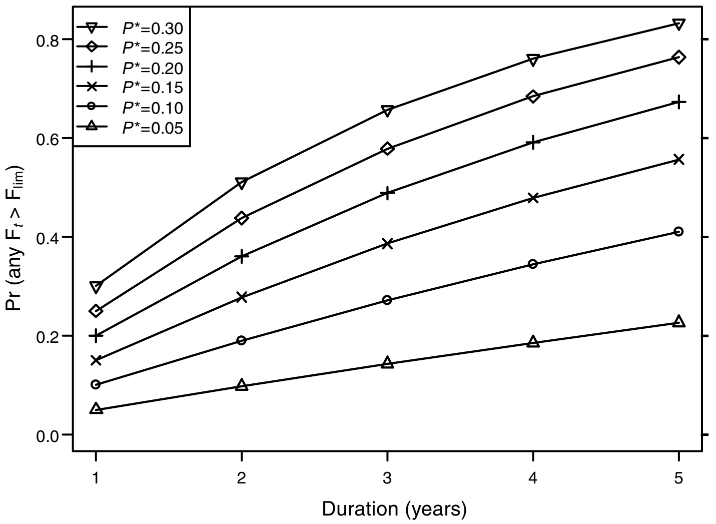

Figure 1

Probability of overfishing in at least one year [Pr(any $F_t > F_{\text{lim}}$)] as a function of time duration, assuming independence among years. Probabilities computed for different levels of annual risk P^*.

Materials and methods

Probability-based approach to setting catch levels (PASCL)

The proposed method acts as a harvest-control rule. It is a probability-based approach to setting catch levels (PASCL), incorporating uncertainties in future stock dynamics, assessment results, and management implementation. Given these uncertainties, PASCL sets annual target levels of catch consistent with the level of risk considered acceptable by managers. The method is based on the ratio-extended approach to setting target reference points (REPAST) of Prager et al. (2003), but is considerably revised 1) to establish reference points in catch, rather than in fishing mortality rate, and 2) to add a stock-projection component, which is needed to set catch for more than one year after a stock assessment. The new method is a general framework that can incorporate details of almost any stock that is assessed. It is illustrated with gag (*Mycteroperca microlepis*), a grouper found off the southeastern United States.

Uncertainty in stock dynamics is represented by a stochastic projection model. The projection allows the setting of annual catch levels for more than one year and, if necessary, can account for a lag between the final year of assessment data and the first year of management implementation. The projection model need not carry the assumption of equilibrium dynamics and can include any source of process or estimation uncertainty deemed appropriate, as with projections commonly used in fishery management. Sources often considered are recruitment dynamics and initial numbers of fish at age. Modeling nonequilibrium population dynamics, as here, is critical for developing harvest strategies (Hauser et al., 2006).

Stock assessment results generally include estimates of uncertainty. A key stock assessment result used in PASCL is the estimate of F_{lim}, the limit reference point of fishing mortality rate (F) and its associated uncertainty, described by a probability density function (PDF), which can be either parametric or nonparametric. If a PDF of F_{lim} is unavailable, PASCL can use a point estimate, but ignoring that source of uncertainty can make overfishing more likely (Prager et al., 2003). Another basic assessment result, the estimate of stock abundance at age (with the corresponding estimate of uncertainty), is used to initialize stock replicates in stochastic projection with PASCL.

Uncertainty in implementation stems from managers having only partial control of the catch (Rosenberg and Brault, 1993; Caddy and McGarvey, 1996; Prager et al., 2003). A target catch may not be met precisely if catch is monitored with delay, catch is managed indirectly through input controls, regulations are poorly enforced, or fishing behavior is unpredictable.

In PASCL, as in REPAST (Prager et al., 2003), the level of risk acceptable to managers (P^*) is quantified and explicit. In our study, risk is defined as the probability of overfishing in any year t, i.e., as $\Pr(F_t > F_{\text{lim}})$. A small value of P^* corresponds to risk-averse management. Always, $P^* < 0.5$ should hold, because at $P^* = 0.5$, overfishing is expected in half of all years. When P^* is defined as a constant probability, the risk of overfishing in at least one of T years grows with the time horizon as $1-(1-P^*)^T$ (Fig. 1).

In a simple formulation, the limit fishing mortality rate F_{lim} could be represented by a point estimate. Then, the probability (here equated to risk) of overfishing in year t would be a function of F_{lim} and the PDF of F_t (ϕ_{F_t}):

$$\Pr(F_t > F_{\text{lim}}) = \int_{F_{\text{lim}}}^{\infty} \phi_{F_t}(F)\,dF = 1 - \Psi(F_{\text{lim}}), \tag{1}$$

where $\Psi(F_{\text{lim}})$ = the cumulative distribution of F_t evaluated at F_{lim}.

A catch level can then be set to position the distribution of F_t so that the desired risk is achieved; i.e.,

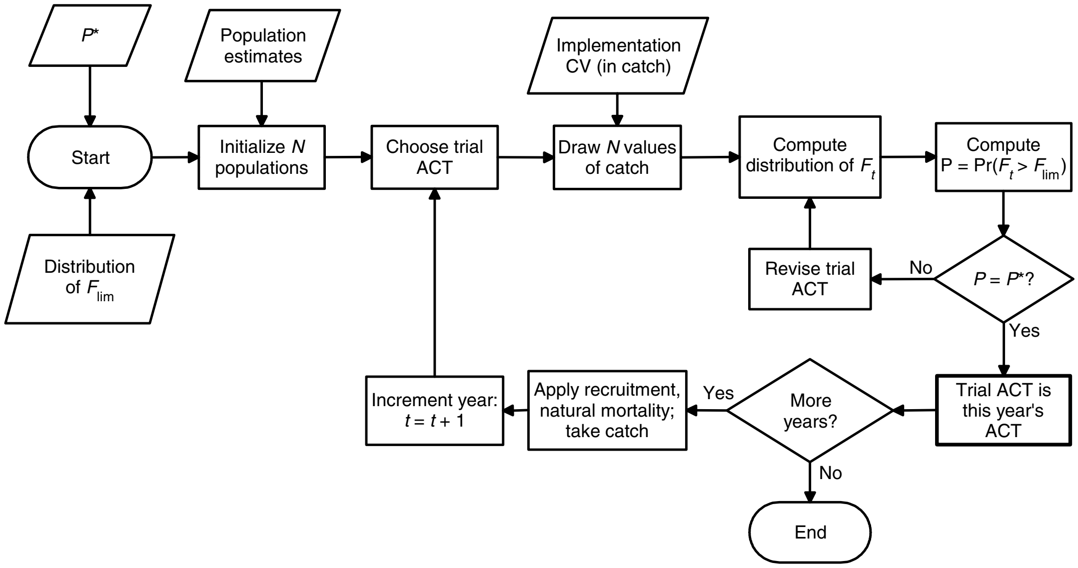

Figure 2

Flowchart of method to compute annual catch level. P^* is the acceptable risk of overfishing, F_{lim} is the limit reference point in fishing mortality rate, N is the number of replicate projections, ACT is the target annual catch level, CV is the coefficient of variation of management implementation, F_t is the fishing mortality rate in year t of a single projection replicate, and P=Pr(F_t>F_{lim}) is the probability of overfishing in year t associated with a trial ACT.

Pr(F_t>F_{lim})=P^*. That catch level becomes the annual catch level in the sense of the MSRA.

The full formulation used here is slightly more complex (and realistic) in that F_{lim} is described by its PDF, $\phi_{F_{\text{lim}}}$. Then, the probability of overfishing is computed as

$$\Pr(F_t > F_{\text{lim}}) = \int_0^{\infty} \left[\int_F^{\infty} \phi_{F_t}(\theta) d\theta \right] \phi_{F_{\text{lim}}}(F) dF, \tag{2}$$

where θ = a dummy variable.

Equation 2 is the weighted sum of probabilities computed by Equation 1 for all possible values of F_{lim}. Again, the distribution of F_t can be positioned so that Pr(F_t>F_{lim})=P^*.

An assumption of Equation 2 is that F_{lim} and F_t are independent. If correlation is observed or suspected, the probability of overfishing could be computed from the bivariate PDF $\phi_{F_{\text{lim}},F_t}$,

$$\Pr(F_t > F_{\text{lim}}) = \int_0^{\infty} \int_F^{\infty} \phi_{F_{\text{lim}},F_t} d\theta dF. \tag{3}$$

Although Equation 3 is more general, estimation of $\phi_{F_{\text{lim}},F_t}$ from data may seldom be possible. Fortunately, in many applications, Equation 2 will be a suitable approximation (see *Discussion* section).

The goal of PASCL is to set annual catch levels such that Pr(F_t>F_{lim})=P^* in each year of a multiyear sequence. Extensions from the formulations described by Equations 1 and 2 are twofold: 1) use of output controls (catches) for management, and 2) a management time frame of more than one year. In what follows, we assume that PASCL is used to compute annual catch targets (ACTs).

The approach is implemented through a projection model (Fig. 2) with the following steps:

1. Initialize N replicates of the stock, each different in abundance and age structure, to reflect uncertainty in the estimated current state of the stock.
2. Given implementation uncertainty in controlling catch, each ACT will be the central tendency of a probability distribution ϕ_C. Choose a trial value of μ, and draw N values $\{C_1 \ldots C_N\}$ from the corresponding distribution. Catch C_1 is the catch taken from stock replicate N_1, C_2 from N_2, and so forth.
3. To combine uncertainties in the state of the stock and implementation, compute for each replicate the fishing mortality rate that yields C_n. This produces N values of F_t to define its empirical probability density (ϕ_{F_t}).
4. Given ϕ_{F_t} and $\phi_{F_{\text{lim}}}$, compute P=Pr(F_t>F_{lim}) from Equation 2.
5. Using a numerical optimization method, adjust μ until P=P^*. The adjusted μ is that year's ACT.

6 Project each replicate one year forward by applying recruitment and natural mortality and taking catch C_n.
7 Repeat steps 2–6 for T years.

In general, duration T of the projection will extend until ACTs based on the next assessment can be implemented. The preceding procedure gives an ACT for each year in the period, and the annual probability of overfishing is kept at P^*.

Setting catch levels of gag

To illustrate the method, we applied PASCL to the gag stock off the southeastern United States. The stock was most recently assessed in 2006 from data through 2004 and a statistical catch-age model (Quinn and Deriso, 1999) including the Beverton–Holt spawner-recruit model (Beverton and Holt, 1957). The stock was estimated to be experiencing the effects of overfishing with a biomass at nearly 90% of that at maximum sustainable yield (SEDAR, 2006). To implement PASCL, we devised a stochastic projection model with structure identical to the age-based assessment model (SEDAR, 2006), in which landings and discards were computed from the Baranov (1918) catch equation. The parameter values chosen were those used or estimated in the assessment.

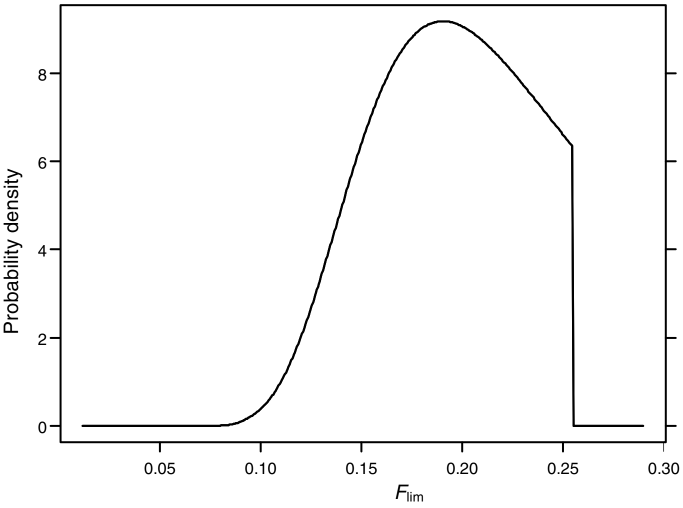

Figure 3

Probability density ($\phi_{F_{\text{lim}}}$) of the limit reference point (F_{lim}), defined here as the fishing mortality rate at maximum sustainable yield.

The projection included two sources of uncertainty in stock dynamics. One was stochasticity in recruitment, assumed to be lognormal about the estimated Beverton-Holt spawner-recruit model, with parameter values from the assessment. The other was uncertainty in the estimated final numbers at age ($\hat{N}_{\text{a},2005}$), which become the initial numbers at age in our example ($N_{\text{a},2005}$). In some applications, the variance of $N_{\text{a},2005}$ would be estimated during the assessment, but SEDAR (2006) provided only point estimates. To include uncertainty, we assumed that multiplicative error in the initial numbers at age followed a lognormal distribution with mean (in log space) of zero and a standard deviation equal to that of recruitment ($\hat{\sigma}_R$):

$$N_{a,2005} = \hat{N}_{a,2005}\exp(\nu), \tag{3}$$

where $\nu \sim N(\mu=0,\ \sigma=\hat{\sigma}_R)$.

This approach accounts for uncertainty in initial conditions, while maintaining strong year classes estimated in the terminal year of the assessment.

The first year of the projection was 2005, and new regulations on catch levels were implemented in 2008. For the projection during the premanagement years (2005–07), we applied a fixed level of landings, set to the geometric mean of landings from 2002 through 2004. The duration of the projection was 10 years: three premanagement years followed by seven years of managed catch levels (landings plus discard mortalities). Presumably, this duration is generous, spanning a period until the next assessment.

The stochastic projection model was used to generate N=10,000 replicate stocks differing in abundance and age structure. This variation, along with imprecise management implementation, led to N=10,000 values of fishing mortality rate in each year, which were used to characterize the fishery's annual probability density of F_t. These densities (ϕ_{F_t}) were quantified nonparametrically through kernel density estimation with Gaussian kernel and bandwidth equal to the kernel's standard deviation (Venables and Ripley, 2002).

The limit reference point in F was set equal to F_{MSY} (Mace, 2001). For this example, the probability density of F_{MSY} ($\phi_{F_{\text{lim}}}$) was estimated after the assessment through Bayesian analysis of the Beverton-Holt spawner-recruit model, accounting for uncertainty in model parameters. A prior distribution was specified for steepness (h), the parameter controlling how quickly recruitment approaches its unfished level as spawning biomass increases. This prior distribution was based on meta-analysis of steepness values (Myers et al., 1999) from species similar to gag. Species included were those considered to be periodic spawners, as defined by Rose et al. (2001), and limited to marine or anadromous demersal fishes, excluding rockfish (*Sebastes* spp.) because of their uncharacteristically low steepness values. The estimated prior distribution was lognormal (SEDAR, 2004):

$$h = \exp(x) : x \sim N(\mu = -0.33, \sigma = 0.28). \tag{4}$$

The resulting posterior distribution of F_{MSY} described $\phi_{F_{\text{lim}}}$ for use in PASCL (Fig. 3). In this example, $\phi_{F_{\text{lim}}}$

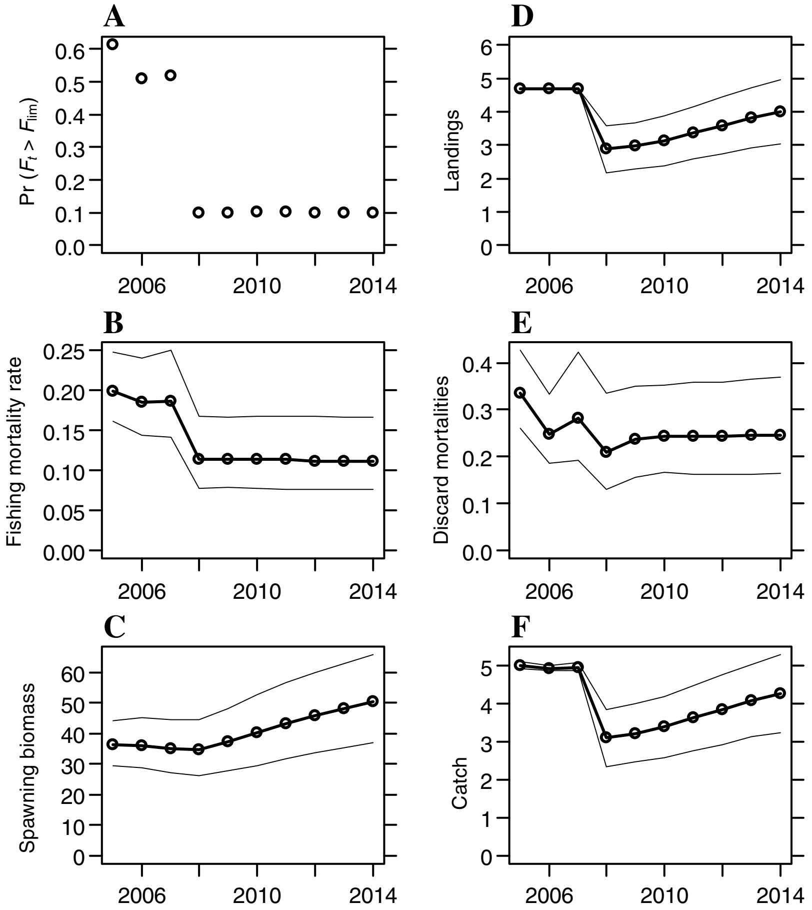

Figure 4

Example projection with managed risk of overfishing set at P^*=0.1 and uncertainty in management implementation described by its coefficient of variation CV=0.2. (**A**) Probability of overfishing, (**B**) annual fishing mortality rate, (**C**) spawning biomass (100 metric tons [t]), (**D**) landings (100 t), (**E**) dead discards (100 t), (**F**) annual catch level (100 t). In B–F, results are presented as medians (thick lines, circles), along with 10th and 90th percentiles (thin lines), from N=10,000 projection replicates.

approaches zero quickly on the right because F_{MSY} is connected tightly with steepness, a bounded parameter with positive probability at its upper bound.

To allow uncertainty in management implementation, the annual catch level was assumed to follow a normal distribution with the mean equal to the target annual catch and coefficient of variation (CV) equal to a preset value. In some applications, the CV of implementation might be estimated from data on performance of the fishery; in this application we considered values of 0.1, 0.2, and 0.3, with a focus on the assumption of CV=0.2.

The final requirement of PASCL is to specify the allowable risk of overfishing. This analysis considered six different levels: $P^* \in [0.05, 0.10, 0.15, 0.20, 0.25, 0.30]$.

Results

During the premanagement period (2005–07), overfishing was projected to occur in at least half of the projections, and thereafter, at the acceptable P^* (Fig. 4A). Because the probability of overfishing in the premanagement period was higher than P^*, the fishing mortality rate was reduced when annual catch targets took effect (Fig. 4B). This allowed spawning biomass to increase (Fig. 4C). With nearly constant F, the increase in biomass provided for an increase in catch, composed mostly of live landings but also dead discards (Fig. 4, D–F). Catch within a year varied by replicate, reflecting uncertainty in management implementation, but by design was centered on the annual catch level (Fig. 4F).

Greater precision in management implementation reduced the variance of F_t for a given catch, which in turn allowed higher fishing mortality rates without an increased probability of overfishing (Fig. 5A). The higher rates then translated into larger annual catch levels (Fig. 5B).

In general, higher P^* was associated with larger catch (Fig. 6A). Biomass increased over time for all P^* examined, but more quickly when risk of overfishing was smaller (Fig. 6B). Consequently, catch increased more quickly for smaller risk, and thus the overall range of catch shrank over time across levels of P^*.

Discussion

The proposed probabilistic approach to setting annual catch levels, PASCL, is quite flexible. It incorporates many of the projection methods common in stock assessment, which can be based on size-structured, age-structured, or unstructured population models. It can incorporate any sources of uncertainty considered important; for example, environmental influences, demographic stochasticity, and multispecies effects. Our work extends common methods by explicitly considering uncertainty in the limit reference point, uncertainty in management implementation, and the level of risk acceptable to managers.

A limit reference point used with PASCL can be a single value, such as F_{MSY} or a proxy for F_{MSY}, but it need not be a single value. For example, the F_{lim} used to manage U.S. west coast groundfish is a function of standing biomass (Punt, 2003). Uncertainty in the limit, whether a single value or function, could be modeled with any appropriate distribution. Similarly, uncertainty in management implementation can be incorporated with flexibility.

Choice of harvest-control rules

PASCL will not be the best choice for setting annual catch levels in every stock. In particular, data-poor stocks will likely require a different approach, such as assemblage management or the use of expert judgment. For rebuilding overfished stocks, other projection approaches may be more suitable (Jacobson and Cadrin, 2002; Punt, 2003). During rebuilding, harvest policies are typically based on the probability of stock recovery within a specified time horizon, rather than on the less restrictive constraint of preventing overfishing. As overfished stocks recover, however, a method such as PASCL could be applied to prevent the stock from another decline and the need for future rebuilding plans.

In one school of thought, choice of a harvest-control rule should be based on the likelihood of meeting long-term management objectives. In this regard, the efficacy of PASCL could be compared to that of other control rules by simulating the assessment and management processes in conjunction with stock dynamics (Cooke, 1999; Punt, 2003). Such management strategy evaluations can be useful for shedding light on which control rules work best under various conditions. However, they are complex, and thus difficult to program, verify, explain, and modify as circumstances change. Moreover, most fishery management is in fact based on short-term to medium-term considerations, and management strategies are likely to change to meet social, biological, or environmental conditions. When a major objective of management is to avoid overfishing, PASCL should be quite effective, and it may simultaneously meet more complex objectives. An advantage of simple control rules such as PASCL is that they can be applied after each assessment without major redesign.

In our example, we computed annual catch levels as targets. With slight modification, the method can be used to compute annual catch limits and targets simultaneously. For example, a catch limit (or acceptable biological catch) might be set to prevent overfishing based on scientific uncertainty (e.g., process and estimation error), and a catch target might then be set lower than the limit to

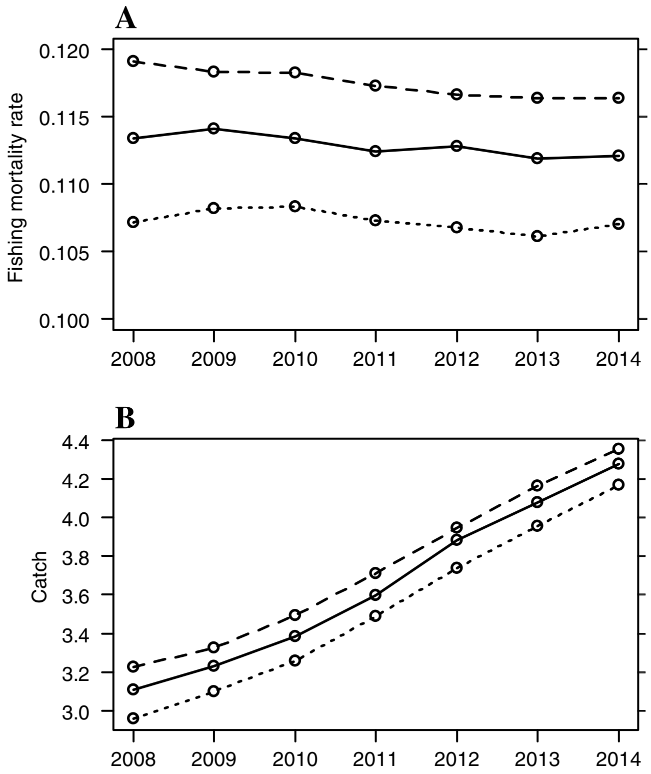

Figure 5

Median annual (**A**) fishing mortality rate and (**B**) catch level (100 t) from projections with managed risk of overfishing set at $P^*=0.1$ and uncertainty in management implementation, defined by the coefficient of variation CV, set at CV=0.1 (dashed), CV=0.2 (solid), or CV=0.3 (dotted).

account for the implementation of uncertainty. In a projection over multiple years, however, limits and targets should remain coupled, because simulated catch feeds back to abundance levels and thus affects catch levels (limits and targets) in the next year.

Correlation of fishing mortality rates

PASCL, as implemented through Equation 2, implicitly treats the two variables F_{lim} and F_t as independent. In some applications, the two may be correlated. To examine this correlation, we conducted a simulation analysis, in which an age-structured population model was used to generate data that were then used in a catch-age assessment model. In the population model, parameter values representing natural mortality, somatic growth, maturity, fishery selectivity, steepness, recruitment variability, landings, and indices of abundance were generated at random by using levels from other simulation studies (Maunder and Deriso, 2003; Williams and Shertzer, 2003). For simplicity, the simulation included one fishery and one index of abundance. The population was initiated near its unfished state and was subjected to a 27-year linear increase in fishing mortality ranging from 0 to 2 times the rate at F_{MSY} (F_{lim}). Based on 10,000 simulations, the assessment output provided no evidence of correlation between estimates of F_{lim} and terminal-year F_t (r=−0.004, P=0.694), supporting the assumption of independence. In any given application, however, if correlation between F_{lim} and F_t is considered important, PASCL could be applied by using Equation 3.

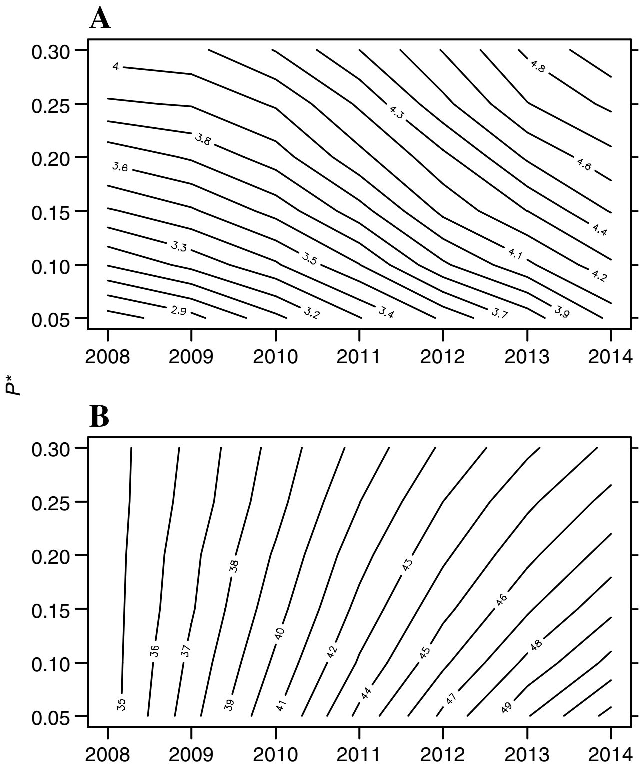

Figure 6

Contours of (**A**) median annual catch levels (landings plus discard mortalities) and (**B**) median spawning biomass, both in units of 100 metric tons, and plotted as functions of time (years) and the acceptable risk of overfishing (P*). Uncertainty in management implementation was set at CV=0.2.

Implementation uncertainty and bias

Uncertainty in implementation is a common, but often ignored, reality of natural resource management (Johnson et al., 1997). This source of uncertainty was quantified here by a normal distribution with an assumed coefficient of variation. In some cases, the distribution could be estimated from data on performance of the fishery—a scenario we expect to become more common as annual catch targets are applied more widely. Our example showed that more precise management allowed higher fishing rates, and thus larger catches, without increased probability of overfishing. Similarly, larger catches would result from more precision in stock dynamics or assessments. This outcome underscores the economic benefits of timely monitoring, enforcement, and compliance.

A notable feature of PASCL is that managers may choose the level of risk that they consider acceptable. This choice could reflect socio-economic considerations, in addition to biological factors such as productivity and vulnerability of the stock. In some cases, higher risk of overfishing may be desired, for example if short term loss of yield outweighs long-term benefits (Shertzer and Prager, 2007). In other cases, managers may be more precautionary. Either way, establishing the level of risk as an explicit choice increases transparency in the management process.

A simplifying assumption of our application was that annual catch, although imprecise, was centered about the target catch level. In many fisheries, however, the distribution of annual catch may be asymmetric in either direction of the target. Such asymmetric distributions can easily be accommodated in PASCL. When annual catch falls above or below the target, managers may consider adjusting target catch in subsequent years accordingly.

Conclusion

Over the next several years, as science responds to legislation, a body of practice will be developed to implement annual catch limits and targets. In managing U.S. federal fisheries, new approaches must address the MSRA requirements to end and prevent overfishing. The

PASCL framework proposed here is intended to satisfy these requirements, and it certainly can be applied more broadly in fisheries where the management of catch levels has the objective of avoiding overfishing.

Acknowledgments

The authors are grateful for the support of the National Marine Fisheries Service Southeast Fisheries Science Center and for comments from J. Bence, P. Conn, D. Vaughan, and anonymous reviewers.

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