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[Article]

Graphical Evaluation of Fishery Status Using a Likelihood Inference Approach

YAN JIAO
Department of Fisheries and Wildlife Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0321, USA

KEVIN REID
Ontario Commercial Fisheries Association, Box 2129, 45 James Street, Blenheim, Ontario N0P 1A0, Canada

TOM NUDDS
Department of Integrative Biology, University of Guelph, Guelph, Ontario N1G 2W1, Canada

ERIC SMITH
Department of Statistics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, USA

Abstract.—We present a graphical method that uses a statistical likelihood approach to summarize evidence and risk in fishery status evaluation. The graphical method is based on the surplus production model and shows the fishery status as regions and colors on graphs. Two fishery status graphs are used: one is based on the comparison between observed catch and catch at the fishing mortality level corresponding to maximum sustainable yield; the other one is based on the comparison between observed catch and catch at the surplus production level. The graphical statistical likelihood approach quantifies the strength of evidence in supporting different hypotheses of fishing status as regions in the status graphs. A simulated hypothetical fishery is given as an example. Results are graphically presented to show the exploitation status of the fishery, and they compare favorably with those from a composite risk assessment method. This graphical statistical likelihood approach may improve the communication of knowledge and evidence among scientists, fishery stakeholders, and management agencies and may provide a better understanding of current fishery status.

The emerging requirement for transparency in the fishery management process (Decker and Krueger 1993; Starr et al. 1998) necessitates approaches and tools that can convey the complicated theory of uncertainty and risk to stakeholders and managers. Science plays a key role in helping to communicate stock assessment results and management strategies to a mix of stakeholders and users of a resource (Watson-Wright 2007). This issue is increasingly important in fisheries management, particularly with the emergence of risk analysis as a key component in the process of setting total allowable catch. The understanding of complex concepts and methods (e.g., probability theory, likelihood, risk, and uncertainty) is quite varied among the diverse groups involved in the management of a fishery. Fisheries science professionals can be expected to have a greater level of understanding of these concepts and methods than stakeholders such as anglers and commercial fishermen. Academic professionals are expected to have a very high level of understanding and to use or invent advanced research methods that may be viewed as complicated by stakeholders and other groups. The objective of this study is to develop an approach to effectively communicate the complexities of risk and evidence in fisheries management in a way that is relatively simple and easy to understand and does not require professional-level technical knowledge, yet retains technical details.

The status of a fishery stock is often determined by comparing an indicator reference point (e.g., current fishing mortality F) with a management reference point (e.g., F at maximum sustainable yield [MSY], F_{msy}). Both references are likely subject to large uncertainty (Helser et al. 2001; Jiao et al. 2005). Current fishery status evaluation methods in the United States and many other countries use harvest control rules for promoting public awareness of the status of marine and freshwater fisheries and for harvest decision making by management agencies (Restrepo et al. 1998; Restrepo and Powers 1999). Two metrics of fishing status are F/F_{msy} and the ratio of current biomass B to biomass at

* Corresponding author: yjiao@vt.edu

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MSY (B_{msy}). Overfishing is indicated when F/F_{msy} is greater than 1, and an overfished population is indicated when B/B_{msy} is smaller than 1. While the metrics are useful indicators of status, they do not directly include uncertainty about the population status. The necessity of incorporating such uncertainties in determining the status of fisheries has been widely discussed (Hilborn and Walters 1992; Ludwig et al. 1993; Walters and Maguire 1996). Fisheries management requires a close examination of the role that uncertainty plays in determining the status of a fish stock and in managing fisheries to reduce the likelihood of overexploitation (Ludwig et al. 1993; Myers and Worm 2003).

Many risk-based decision-making analyses consider uncertainty from either an indicator reference point or a management reference point but not from both (FAO 1995; Quinn and Deriso 1999). Jiao et al. (2005) applied composite risk assessment to fisheries stock assessments to estimate the risk of overfishing and of a stock being overfished. This approach incorporated uncertainties both from the indicator reference point and the management reference point. However, this approach did not connect risk-based decision making to the harvest. The commonly used approach (FAO 1995; SAFMC 2006) for diagnosing whether F/F_{msy} is greater than 1 and whether B/B_{msy} is less than 1 to determine fishery status does not consider uncertainties in the estimation of F/F_{msy} and B/B_{msy} and does not connect the fishery status to harvest (or catch and quota).

During communication of the Jiao et al. (2005) approach to the Ontario Commercial Fisheries Association, the idea of linking the fishery status evaluation with the harvest and the population size surfaced. Catch C at F_{msy} ($C_{F\mathrm{msy}}$) is generally easier to understand by stakeholders than is F_{msy} because catch is of much higher concern, is directly related to economic benefit, and is comparable with the reported catch, which is more straightforward and easier to understand than F. Another reason that $C_{F\mathrm{msy}}$ was chosen is because F_{msy} is used as the management reference point in many fisheries in the world. Whether F_{msy} is a good reference point or not is beyond the scope of this paper. A risk assessment that fully considers uncertainty of F_{msy} and F (Jiao et al. 2005), or the approach described here, is consistent with the use of F_{msy} as a limit reference point against uncertainty. In addition to F_{msy}, catch was compared with the surplus production curve, which remains a useful way of assessing long-term risk since any continued catch level above the surplus production curve is unsustainable and results in a declining biomass (Roughgarden and Smith 1996).

Decisions about the status of a fishery using reference points should be based on the evidence associated with these reference points. In the statistical approach, evidence is typically associated with data, the probability model for the data, and the resulting likelihood of the data (Royall 1997; Taper and Lele 2004). For example, when evaluating a hypothesis about a fishery, the likelihood of the data assuming the hypothesis is true gives a measure of evidence for or against the hypothesis. The law of likelihood provides a means for evaluating the evidence for one hypothesis relative to another. Specifically, if we have two hypotheses about fisheries status, H_1 and H_2, and using $L(\mathrm{data}\,|\,H)$ to represent the likelihood of the data given the hypothesis, then

$$\frac{L(\mathrm{data}\,|\,H_1)}{L(\mathrm{data}\,|\,H_2)}$$

measures the evidence in favor of H_1 relative to H_2.

In many instances, hypotheses are described in terms of a parameter, and the evidence for a hypothesis may be interpreted relative to the optimal value of the parameter. For example, in evaluating the hypothesis H_0: $\theta = \theta_0$, the likelihood ratio

$$\frac{L(\mathrm{data}\,|\,\theta_{\mathrm{MLE}})}{L(\mathrm{data}\,|\,\theta_0)}$$

quantifies the strength of evidence supporting a value of a parameter (or supporting a hypothesis) relative to the maximum likelihood estimate (MLE), θ_{MLE}. Values of the parameter that are supported by the data (i.e., close in likelihood to the MLE) may be used to calculate a likelihood ratio confidence interval (LRCI). The LRCI plot provides a graphical summary of the evidence in the data, and the likelihood ratios for possible fishery statuses (e.g., hypotheses) may be used to represent the strength of the hypothesized statuses (Owen 1990; Royall 1997; Taper and Lele 2004). The likelihood inference method incorporates uncertainties through the likelihood. Likelihood calculations in single-parameter situations are straightforward. In multiparameter situations, the set of parameters is often divided into a set of parameters of interest and a set of "nuisance" parameters (parameters not of immediate interest; Royall 1997). The calculation is then based on a likelihood that removes the influence of the nuisance parameters through the use of either marginal likelihoods, conditional likelihoods, or profile likelihoods (Edwards 1992; Royall 1997).

The likelihood inference method is the only school of statistical inference that purely adheres to the likelihood principle (Royall 1997). Likelihood principle essentially states that all evidence (obtained experimentally) about an unknown quantity of parameter(s) is contained in the likelihood function of the parameter(s) from the given data. Furthermore, two likelihood functions contain the same information about the parameter(s) if they are proportional to each other (Berger and Wolpert 1988; Royall 1997). Likelihood inference is interpreted only on the basis of available data. In contrast, frequentist analysis requires a repeated sampling view for interpretation, and Bayesian analysis requires the selection of prior distributions for the parameters and the interpretation is conditional on the selected prior (Wade 1999). A study by Wade (1999) represents an example of recent research in fisheries using the likelihood inference method.

When the likelihood inference approach described in this paper and the composite risk assessment approach were presented to the Ontario Commercial Fisheries Association and to the Lake Erie Committee, the fishermen and some fishery biologists seemed to quickly accept the concept of the likelihood inference approach. A visual method was employed to identify fishery status and the support for status estimation by using regions and colors on graphs (e.g., Hatton 2003). A surplus production model was the basis for stock assessment and risk assessment, allowing the fishery status and its uncertainty to be evaluated. The likelihood inference method (Edwards 1992; Royall 1997; Wade 1999) was used for status evaluation in our graphical approach. The graphical approach seemed to improve the communication of both risk and uncertainty among all groups. Better understanding of the current fishery status helps fishery managers make better decisions and helps other stakeholders understand the rationale for management decisions (Boucek et al. 2001). This improvement in communication was accomplished without loss of the most important technical details required by fisheries professionals.

In this paper, the likelihood method for evaluating a fishery's status is described and applied to a simulated fishery to give an example of assessing the likely history and current status of the fishery. We also applied the composite risk assessment method to the same simulated fishery to assess the risk of overfishing (defined as the probability P that $C > C_{F\text{msy}}$ or the probability that $C >$ catch at surplus production, C_{sp}; Jiao et al. 2005). Results from the proposed graphical method were then compared with the results based on the composite risk assessment. This comparison was done to determine whether the graphical method loses technical information and whether results of the graphical method are consistent with those of an established quantitative risk assessment method.

Methods

The surplus production model.—The surplus production model was used to model the dynamics of the stock abundance. It is widely employed in fisheries and ecology because of its simplicity and moderate data requirements (May et al. 1979; Hilborn and Walters 1992; NRC 1997). Observation error estimators seem to perform better than process error estimators in fitting production models to data (Punt 1988; Hilborn and Walters 1992; Polacheck et al. 1993). The surplus production model corresponding to the observation error estimator includes error in the abundance index and can be written as

$$N_{t+1} = N_t + G_t - C_t, \tag{1}$$

and

$$E(I_t^i) = q_i N_t, \tag{2}$$

where N_t is the stock abundance in year t, G_t is the surplus production of stock abundance in year t, C_t is the catch in numbers in year t, I_t^i is the ith abundance index observed in the fishery or surveys (e.g., catch per unit effort) in year t, q_i is the catchability coefficient of the ith abundance index, and E represents a mathematical expectation.

Surplus production is modeled using the logistic population growth model:

$$G_t = rN_t[1 - (N_t/K)], \tag{3}$$

where r and K are the intrinsic rate of increase and carrying capacity or virgin population in numbers, respectively (Hilborn and Walters 1992).

With the assumption that I_t^i is an independent random variable, model parameters can be estimated by maximizing a likelihood function based on the probability distribution of I_t^i:

$$L_i = \prod_{t=1}^{n_i} p(I_t^i \mid r, K, N_0, q_i), \tag{4}$$

and

$$\text{TLL} = \sum_i \lambda_i \text{LL}_i = \sum_i \lambda_i \log_e(L_i), \tag{5}$$

where L is the likelihood, LL is the log likelihood, TLL is the total log likelihood, n_i is the length of the time series of the ith abundance index, λ_i is the weighting of the ith abundance index (Hilborn and Walters 1992), and N_0 is the initial population size.

In this paper, we present an example using a simulated fishery with one abundance index (see data and simulation fishery section). A likelihood profile approach was used to search for MLEs and associated likelihood intervals (see the section below). A generalized linear model approach (Jiao and Chen 2004) was used to estimate q. The algorithm for this approach has two stages when searching for MLEs over the parameters r, K, and N_0 (Jiao and Chen 2004). In the first stage, population abundance is projected based on the population dynamic equation (1), the productivity equation (3), and the gridded parameters r, K, and N_0. In the second stage, q-values are estimated by application of a generalized linear model to fit the observed abundance and the projected population abundance. We used a lognormal error structure, which yielded homogenous residuals. The likelihood function corresponding to equation (4) for only one index was therefore

$$L = \prod_t \frac{1}{I_t\sqrt{2\pi}\sigma} \exp\left\{-\frac{[\log_e(I_t) - \log_e(qN_t)]^2}{2\sigma^2}\right\}, \tag{6}$$

where σ^2 is the variance of the observation error.

Likelihood inference method.—The likelihood inference method is used in this paper to estimate the uncertainty of the parameters and the status of the simulated fishery. The LRCI for parameters, hypotheses, or both can be obtained from all combinations of parameters ($\theta_{\text{endpoints}}$) that satisfy

$$\frac{L(\text{data} \mid \theta_{\text{MLE}})}{L(\text{data} \mid \theta_{\text{endpoints}})} = k, \tag{7}$$

where k is the critical value that determines the LRCI. For the LRCI of one parameter, a k-value equal to 6.82 is used, which is analogous to a 95% confidence interval in a likelihood ratio chi-square test (Thomas and Grunkemeier 1975; Owen 1990; Edwards 1992; Hilborn and Mangel 1997; Gimenez et al. 2005). For the LRCI of states that require two parameters, we used a k-value equal to 20, which corresponds to a 95% confidence interval in a likelihood ratio chi-square test for the bivariate case (Owen 1990; Gimenez et al. 2005).

The likelihood (equation 6) and likelihood ratio are used to determine confidence intervals as shown above; they also show the strength of evidence for each hypothesis about the fishery status (likelihood ratio of $k \subset [1, \infty]$). The smaller the value of k, the higher the evidence that the corresponding status is supported (Royall 1997). Higher values of k imply more risk-averse management, and lower values of k imply more aggressive or higher-risk management. We incorporated the likelihood ratio of the fishery in each region in the status graphs to communicate evidence for the status.

Likelihood inference method in estimating uncertainty of the fishery status.—The likelihood inference method was used here to estimate the uncertainty of the fishery status represented as status graphs in Figures 1 and 2. Likelihood estimates arising from the set of parameter values for each hypothesis were then compared to discriminate among hypothetical states based on the likelihood ratio (see the flowchart in Figure 3). The uncertainty related to individual parameters and the associations of those parameters can thus be distilled into their combined influence on the dynamics of the population and provide clear implications for risk and sustainability of the fishery states. In this study, the profile likelihood approach (Wade 1999) was used to derive the parameter likelihood profile. The algorithm used was to (1) grid values of the parameters in the model and estimate the corresponding likelihood values; (2) based on each parameter vector in the model, estimate those state variables and parameters not in the model but deduced from the parameter estimates of r, K, and N_0—here, these were N_t, N_{msy} ($=rK/4$), F_{msy} ($=r/2$), C_{sp}($=rN_t[1 - N_t/K]$), depletion ($=N_t/K$), and F_t ($=C_t/N_t$); (3) estimate evidence for alternative hypotheses of stock status (Table 1) that incorporate correlations among stock status and reference points by comparing C with MSY, $C_{F\text{msy}}$, or C_{sp} and comparing N with N_{msy}; (4) repeat steps 1–3 until all the combinations of the gridded values of the parameters are gone through; and (5) estimate the likelihood for each region by searching for the maximum likelihood values over the relative parameters that determine the stock status and result in the identical region in the status graphs (Bowman and Azzalini 1997). Likelihood estimates arising from the parameter vector for each hypothesis can be further compared to discriminate among hypothetical states based on the likelihood ratio test to identify the most likely states (see the flowchart in Figure 3). In most cases, we are interested in one parameter at a time (e.g., θ_1). Therefore, we calculate the profile likelihood $L(\theta_1)$, given by

$$L(\theta_1) = \max_{\theta_2,\ldots\theta_k} [L(\theta_1, \theta_2, \ldots \theta_k)],$$

as follows: for each of the values of the parameter θ_1, the corresponding $L(\theta_1)$ is the value of the likelihood obtained by treating θ_1 as fixed and allowing other parameters ($\theta_2, \ldots \theta_k$) to vary over their ranges. The fixed value of θ_1 and the values of ($\theta_2, \ldots \theta_k$) that maximize the likelihood are substituted into the function to obtain one value of $L(\theta_1)$. The process is repeated over the range of θ_1. For derived parameters, such as $C_{F\text{msy}}$, C_{sp}, and N, the corresponding profile for each fixed value of the parameter is simply a matter of

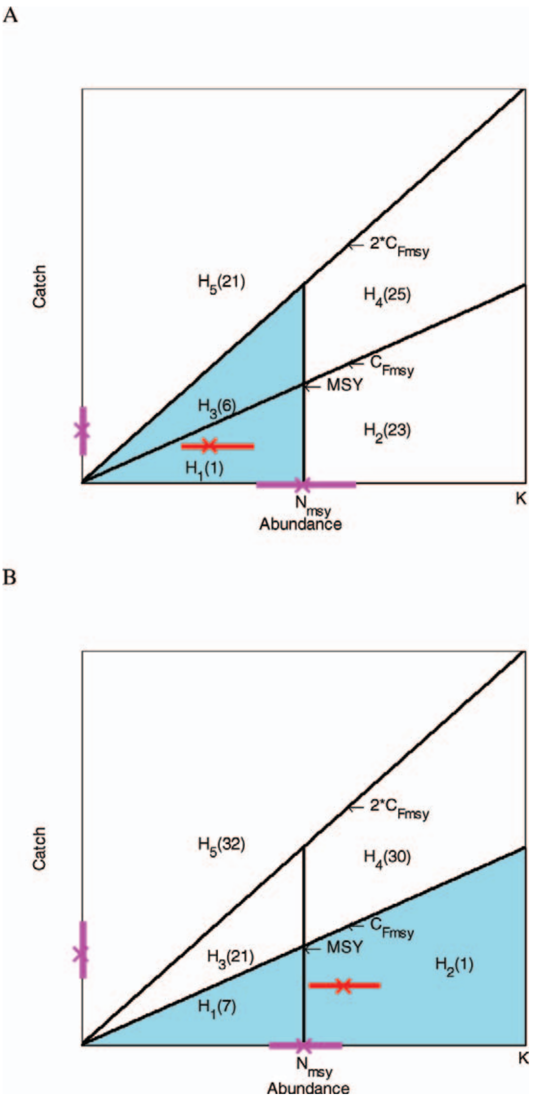

FIGURE 1.—Two examples (**A** and **B**) of fishery status and its uncertainty, with catch C at a fishing mortality level F corresponding to maximum sustainable yield (MSY; i.e., $C_{F\text{msy}}$) as the reference catch level (light blue: likelihood ratio $\leq$ 20; white: likelihood ratio $>$ 20). The likelihood ratio confidence intervals (LRCIs) of population abundance N at MSY (N_{msy}) and $C_{F\text{msy}}$ are shown as thick lines along the x- and y-axes (maximum likelihood estimates are marked with asterisks). The asterisk in the middle of the plot is the best estimate of N (x-value) and the reported C (y-value); the underlying thick red line is the LRCI of N. The numbers in parentheses at the right of region codes H_1 to H_5 (defined in Table 1) are the log likelihood ratios (see Methods).

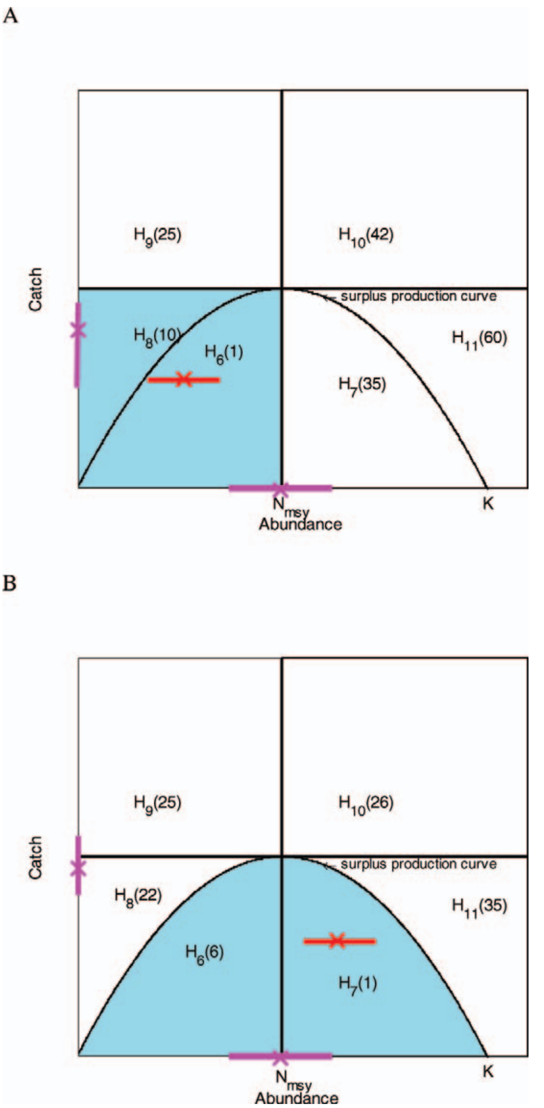

FIGURE 2.—Two examples **(A** and **B)** of fishery status and its uncertainty, with catch C at surplus production (i.e., C_{sp}) as the reference catch level (light blue: likelihood ratio $\leq$ 20; white: likelihood ratio $>$ 20). The likelihood ratio confidence intervals (LRCIs) of population abundance N at maximum sustainable yield (N_{msy}) and C_{sp} are shown as thick lines along the x- and y-axes (maximum likelihood estimates are marked with asterisks). The asterisk in the middle of the plot is the best estimate of N (x-value) and the reported C (y-value); the underlying thick red line is the LRCI of N. The numbers in parentheses at the right of region codes H_6 to H_{11} (defined in Table 1) are the log likelihood ratios (see Methods).

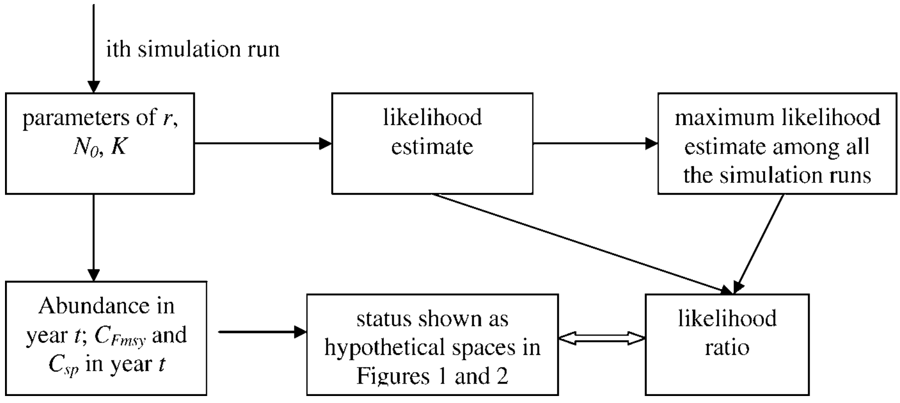

FIGURE 3.—Estimation algorithm used in Figures 1 and 2 (see Methods for symbol definitions).

maximizing over the parameters used in the derivation of $C_{F\text{msy}}$, C_{sp}, and N. By using this algorithm, the uncertainty in both status and reference points was incorporated into the likelihood of each "region." The LRCI can then be estimated using equation (7).

Graphical evaluation of the fishery status.—The stock status can be estimated through an evaluation of the risk of failure. Risk is viewed as the likelihood of failure of management or failure in controlling the fishery. We consider two likelihood measures (corresponding to the management reference points) based on $C_{F\text{msy}}$ and C_{sp}. For each measure, a graphical display is used to evaluate status.

We first developed the approach to graphically evaluate the fishery status by comparing catch with $C_{F\text{msy}}$ (status graphs in Figure 1). In Figure 1, the areas of the graph surrounding the various reference lines can be regarded as distinct hypothesized states of the fishery at any time t. For example, for the graphical region labeled H_1 (i.e., hypothesized state), the model provides the likelihood that the fishery is in the given region of H_1 (i.e., $N <$ abundance at MSY [N_{msy}]; $C < C_{F\text{msy}}$). The state of the fishery can be determined by comparing the catch with $C_{F\text{msy}}$ or with $2 \times C_{F\text{msy}}$ and by comparing the estimated abundance with the N_{msy} given model parameters. The graphical regions (H_1 to H_5) are associated with different combinations of catch and abundance and have implications described in Table 1. Direct comparisons between catch and $C_{F\text{msy}}$ and between abundance and N_{msy} do not consider their uncertainty.

We subsequently developed an approach to graphically evaluate fishery status by comparing catch with C_{sp} (status graphs in Figure 2). In Figure 2, areas of the graph surrounding reference lines again represent

TABLE 1.—Hypotheses (H) regarding regions in the status graphs (Figures 1, 2, 6) and their implications for fishery and population status (C = catch; F = fishing mortality; MSY = maximum sustainable yield; sp = surplus production).

Status	Region	Corresponding hypothesis for the region	Implications for fisheries status
$C_{F\text{msy}}$	H_1	$C < C_{F\text{msy}}$; $N < N_{\text{msy}}$	Population size N is low but will increase because of low exploitation; relatively low risk of population declining
	H_2	$C < C_{F\text{msy}}$ $N > N_{\text{msy}}$	Population size is high, but exploitation rate is not high; N may decrease to N_{msy}; low risk of population declining
	H_3	$C_{F\text{msy}} < C < 2C_{F\text{msy}}$; $N < N_{\text{msy}}$	Population size is low, and overexploitation occurs; high risk of population declining
	H_4	$C_{F\text{msy}} < C < 2C_{F\text{msy}}$; $N > N_{\text{msy}}$	Population size is high, and overexploitation occurs; moderate risk of population declining
	H_5	$C > 2C_{F\text{msy}}$	Overexploitation is very high; high risk of population declining
C_{sp}	H_6	$C < C_{\text{sp}}$; $N < N_{\text{msy}}$	Population size is low, and exploitation is low; N will increase; relatively low risk of population declining, but caution needed because of Allee effect when N is very small
	H_7	$C < C_{\text{sp}}$; $N > N_{\text{msy}}$	Population size is high, but exploitation is low; very low risk of population declining
	H_8	$C_{\text{sp}} < C <$ MSY; $N < N_{\text{msy}}$	Population size is low and will decrease; very high risk of population declining
	H_9	$C >$ MSY; $N < N_{\text{msy}}$	Population size is low and will decrease; extremely high risk of population declining
	H_{10}	$C >$ MSY; $N > N_{\text{msy}}$	Population size is high but will decrease to MSY level; moderate risk of population declining
	H_{11}	$C_{\text{sp}} < C <$ MSY; $N > N_{\text{msy}}$	Population size is high and will decrease to N_{msy}; low risk of population declining

distinct hypothesized states of the fishery at any time t (Table 1).

Uncertainties in defining the status of the fishery are shown as regions and colors on the graphs, and these are used to identify the likely relevant status of the fishery. The definition and implications of the hypothesized fishery status in the two status graphing approaches are outlined in Table 1. The implications for the fishery status are also explained in Table 1.

If the maximum among all the likelihood values for different parameter sets in a certain area is within the LRCI, the graphical region is colored light blue (Figures 1, 2). In Figure 1A, regions H_1 and H_3 are light blue, thus representing the states within LRCI supported by the data. White-colored regions (H_2, H_4, and H_5) indicate a likelihood ratio larger than 20, implying that the hypothesized states H_2, H_4, and H_5 are less likely than H_1 or H_3.

The likelihood ratio shows the strength of evidence for each hypothesis about the fishery status. The numbers in the parentheses in each region of these status graphs (Figures 1, 2) are the values of the likelihood ratios of the MLE relative to the hypothesized value; the smaller the likelihood ratio is, the stronger the evidence is in supporting the hypothesis of the fishery status. For example, if the likelihood ratio equals 1, this means that this region has the highest evidence for being the true fishery status; if the likelihood ratio equals 8, this means the strength of evidence for this region to contain the true fishery status is only one-eighth that of the region with the highest evidence.

In Figure 1, the LRCI (based on $k = 6.82$) of the population abundance is shown as a thick line in the middle of the status graph; the LRCI of N_{msy} is shown as a thick line along the x-axis; and the LRCI of C_{Fmsy} is shown as a thick line along the y-axis. The asterisk marker in the middle of the status graph identifies the best estimate of the population abundance (x-value) and the reported catch (y-value), while the asterisk marker in the x-axis identifies the best estimate of N_{msy} and the asterisk marker in the y-axis identifies the best estimate of C_{Fmsy}.

In Figure 1A, plots of estimated C_{Fmsy} and N_{msy} are given along with their LRCIs. The best estimate of fishery status is represented by the asterisk in the middle of the status graph and is plotted along with the associated LRCI. Note that the best estimate of the population abundance is smaller than the best estimate of N_{msy} and that catch is smaller than the best estimate of C_{Fmsy}; however, likelihood inference shows that the population has evidence of being in H_3 if the LRCI based on a k-value of 20 is used (as in this example; i.e., H_3 is in the LRCI since the likelihood ratio for H_3 relative to the maximum is lower than 20). Considering that the population size is low in this case, a precautionary approach is suggested for the short-term future harvest. In contrast, consider Figure 1B. The best estimate of fishery status is represented by the asterisk in the middle of the graph and indicates that the best estimate of population abundance is larger than the best estimate of N_{msy} and that catch is smaller than the best estimate of C_{Fmsy}. It looks like the fishery is underexploited; however, likelihood inference shows that the population has high likelihood of being in H_1 also (i.e., H_1 is in the LRCI, which can be seen from the value of the likelihood ratio of H_1). Considering the fact that overfishing is not happening, a management policy of keeping the current harvest level is suggested for the short-term future harvest instead of an increase.

Similarly, in Figure 2, the LRCI of the population abundance is also shown as a thick line in the middle of the status graph, the LRCI of N_{msy} is shown as a thick line along the x-axis, and the LRCI of C_{sp} is shown as a thick line along the y-axis. The asterisk marker in the middle of the status graph is the best estimate of the population abundance (x-value) and the reported catch (y-value); the asterisk in the x-axis is the best estimate of N_{msy}; and the asterisk in the y-axis is the best estimate of C_{Fmsy}.

In Figure 2A, the best estimate of fishery status is shown by the asterisk in the middle of the graph (i.e., best estimate of $N <$ best estimate of N_{msy}; $C <$ best estimate of C_{sp}). Likelihood inference shows that the population has the highest likelihood of being in H_1 but also has a high likelihood of being in H_8. Considering that population size is low in this case, decreasing harvest would be recommended for the short-term future. In contrast, in Figure 2B the best estimate of fishery status is represented by the asterisk in the middle of the status graph (i.e., best estimate of $N >$ best estimate of N_{msy}; $C <$ best estimate of MSY and C_{sp}). It looks like the fishery is underexploited; however, likelihood inference shows than the population has some evidence of being in H_6, although the highest likelihood is for the population being in H_1. Considering the fact that overfishing is not happening but abundance is not significantly larger than N_{msy}, a management policy of maintaining current catch levels would be recommended for short-term future harvests.

To better explain the fishery status and its uncertainty, contours of the changes in LL, expressed as

$$\text{LL ratio}|_{\text{location}} = \log_e \left[\frac{L(\text{data} \mid \theta_{\text{MLE}})}{L(\text{data} \mid \theta_{\text{location}})} \right],$$

were added to the status graphs. The LL ratio contours quantify changes in fishery status more precisely than

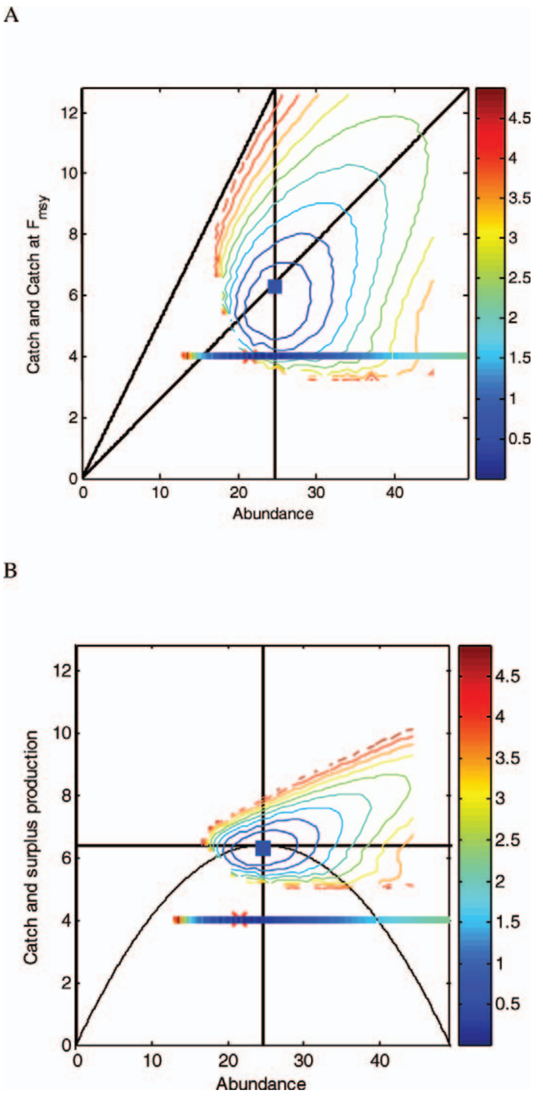

FIGURE 4.—The fishery status for simulation year 1980 and its uncertainty, shown as contour plots in the status graphs: **(A)** log likelihood (LL) ratio contours of population abundance N at maximum sustainable yield (MSY; i.e., N_{msy}) and catch C at a fishing mortality level F corresponding to MSY (i.e., C_{Fmsy}); the square marker is the maximum likelihood estimate (MLE) of N_{msy} (x-value) and C_{Fmsy} (y-value); **(B)** LL ratio contours of N_{msy} and C at surplus production (i.e., C_{sp}); the square marker is the MLE of N_{msy} (x-value) and C_{sp} (y-value). The asterisk on each graph is the MLE of the estimated N (x-value) and the reported C (y-value); the thick line is the likelihood ratio confidence interval of N. The color bar at the right of each panel represents the LL ratios (see Methods).

the colored-block graphs but are not as simple and direct (Figure 4). Figure 4A shows the LL ratios of N_{msy} and C_{Fmsy} as contour plots. Likewise, Figure 4B shows the LL ratio of N_{msy} and C_{sp} as contour plots. The square symbol in either graph is the best joint estimate of N_{msy} (x-value) and C_{Fmsy} (in Figure 4A) or C_{sp} (in Figure 4B; y-value). The asterisk marks the best estimate of the population abundance (x-value) and the reported catch (y-value); the thick line is the LRCI of population size, also color-scaled to the likelihood distribution.

The implications of the risk of population decline and overfishing are summarized in Table 1, and their likelihoods of occurrence are determined by the k-values shown in the status graphs. For example, H_1 and H_2 represent a low risk of population decline and overexploitation, whereas H_3 represents a high risk of population decline and overexploitation. Thus, if H_1 and H_2 have low k-values ($k \rightarrow 1$), then the risk of population decline is low because the data strongly support that the fishery status is in regions H_1 and H_2 of the status graph. On the other side, if H_3 has low k-values ($k \rightarrow 1$), then the risk of population decline is high because the data strongly support that the fishery status is in region H_3 of the status graph.

The results from this graphical approach were compared with those obtained from using a composite risk assessment method (Jiao et al. 2005). The composite risk assessment method estimates the fishery status risk as the probability that the fish stock is experiencing overfishing (i.e., $P[C > C_{Fmsy}]$ when F_{msy} is used as a management reference point; $P[C > C_{sp}]$ when surplus production is used as a management reference point).

Data and the simulated fishery.—A fishery was simulated for 31 years (nominally from 1975 to 2005) based on the following population ecology characteristics: population growth rate r was set equal to 0.5; carrying capacity K was set equal to 50,000,000 fish; and the initial population size N_0 was set equal to 30% of K. Harvest history was simulated based on the following assumptions: first year (1975) catch was at MSY; from 1976 to 1984, the exploitation was 0.75 of F_{msy} with a multiplicative random error from a lognormal distribution (i.e., log-transformed C had an error with a mean of 0 and a coefficient of variation [100 × SD/mean] of 20%). In subsequent years, F was assumed to follow a uniform distribution with variable values: F was assumed to be between 1.0 and 1.5 × F_{msy} from 1986 to 1990; between 1.5 and 2.5 × F_{msy} from 1991 to 1995; between 1.0 and 1.5 × F_{msy} from 1996 to 2000; and between 0.7 and 1.0 × F_{msy} from 2001 to 2005. One abundance index data set was simulated by assuming a q of 0.1×10^{-6}, and the

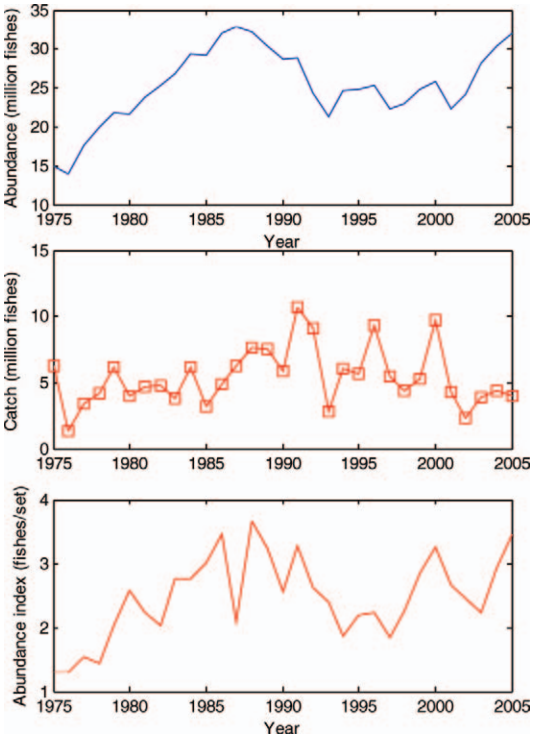

FIGURE 5.—Population abundance (millions of fish), catch (millions of fish), and survey abundance indices (number of fish/set) simulated from 1975 to 2005.

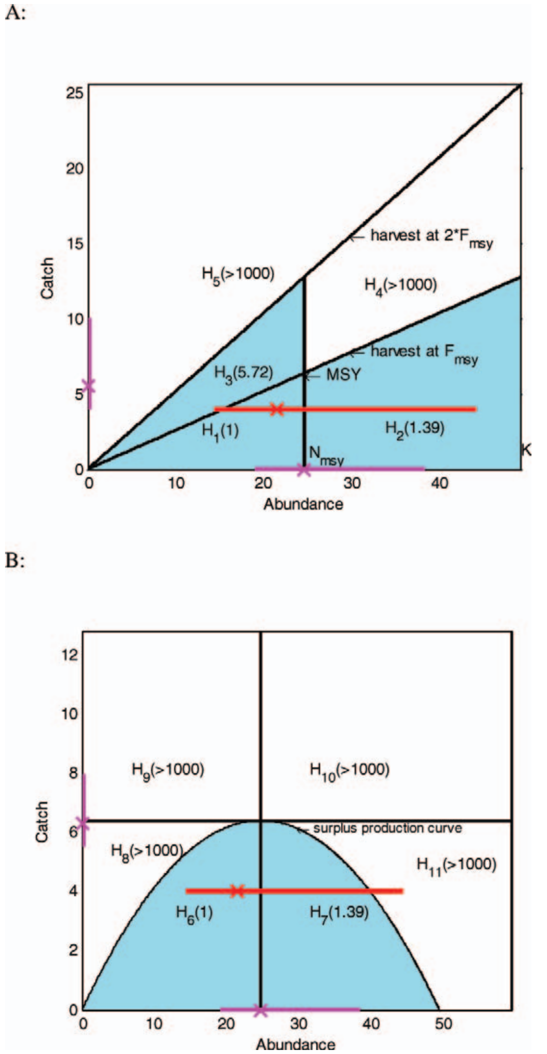

FIGURE 6.—The fishery status in simulation year 1980 and its uncertainty, displayed as status graphs describing **(A)** catch at a fishing mortality level F corresponding to maximum sustainable yield (MSY) and **(B)** catch at surplus production. See Figures 1–3 for further details.

observation error of the abundance index followed a lognormal distribution (i.e., log-transformed abundance index has an error with a mean of 0 and SD of 0.2). The resulting data can be very different for different iterations of the simulation process; we randomly picked one set of catch and abundance index data, as shown in Figure 5.

In this study, we selected years with an end number of 0 or 5 for analysis. The selection was based on convenience and to produce a reasonable number of the figures since our intent was not to assess this simulated example fishery. In practice, assessment of fishery status for all years is suggested based on the proposed approach.

Results

Figures 4 and 6 give the results of the simulated fishery analysis for 1980. The population abundance in 1980 was lower than N_{msy} (Figures 4, 6). There was relatively low likelihood that the fishery exploitation was close to or higher than F_{msy} because the likelihood ratio of the fishery being in region H_1 was 5.72 times that of the fishery being in H_3 (Figures 4A, 6A), and the total catch was below the surplus production because the observed catch was below the LRCI of surplus production (Figures 4B, 6B). Thus, the fishery could be regarded as being overfished, but the population would increase because the surplus production was higher than the reported catch.

The example fishery status assessment in 1975, 1985, 1990, 1995, 2000, and 2005 is shown in Figure 7. The risk of overfishing in 1975 was high because exploitation was higher than $C_{F\text{msy}}$ and C_{sp}. Additionally, the fishery data suggests strong evidence that the fishery was overfished because population abundance was less than N_{msy}. Here, although there is overlap

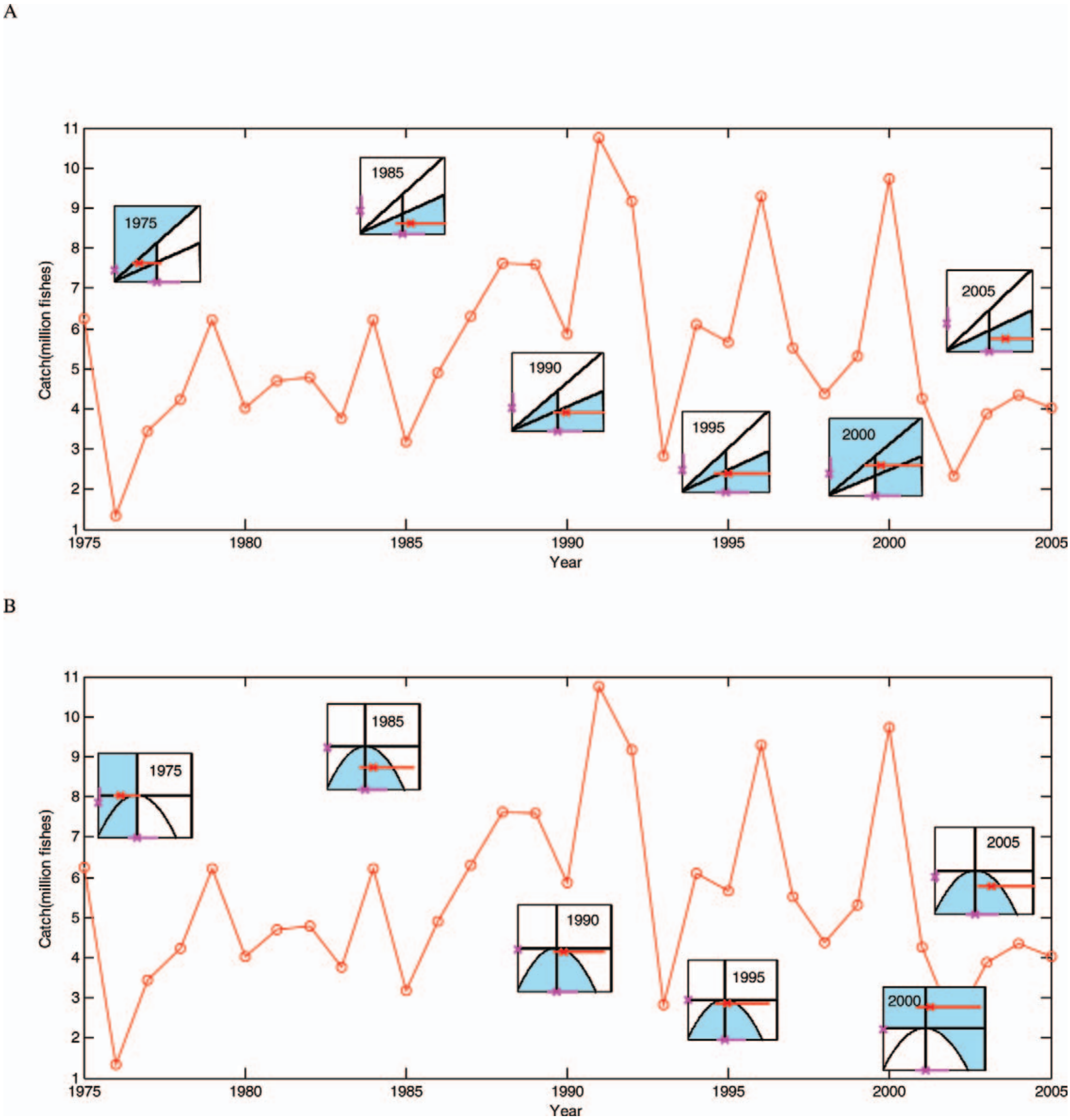

FIGURE 7.—Estimated fishery status in simulation years 1975, 1985, 1990, 1995, 2000, and 2005, corresponding to **(A)** the status graph (Figure 1) describing catch (millions of fish) at a fishing mortality level corresponding to maximum sustainable yield and **(B)** the status graph (Figure 2) describing catch at surplus production.

between the LRCI of population size and that of N_{msy}, there was strong positive correlation (0.82; figure not shown here), hence the likelihood that abundance was greater than N_{msy} was outside of the LRCI. The fishery status in 1985 was close to that of 1980, but the population size had a higher likelihood of being greater than that in 1980. The risk of overfishing in 1990 and 1995 was low because catch was below C_{sp}, though there was some likelihood that exploitation was above F_{msy}. The data indicate some evidence of overfishing, and the population had a roughly equal likelihood of being above or below N_{msy}. In 2000, overfishing obviously happened, given the strong likelihood that catch was above C_{Fmsy} and above C_{sp}. In 2005, the likelihoods of overfishing ($C > C_{Fmsy}$) and the population being overfished ($N < N_{msy}$) were both low even though the likelihood ratio for the population being in H_1 was 9.68 (Table 2).

Combining results from C_{Fmsy} and C_{sp}, the status graph gives a greater sense and better understanding of

TABLE 2.—A comparison between composite risk assessment and the graphical likelihood method. Composite risk assessment estimates the probability of fishery catch C in a given year being larger than C at a fishing mortality level F corresponding to maximum sustainable yield (MSY; i.e., $P[C > C_{F\text{msy}}]$) and the probability of C being larger than C at surplus production ($P[C > C_{\text{sp}}]$). Graphical likelihood inference calculates the likelihood ratio (LR) of the population being in each region of the $C_{F\text{msy}}$ and C_{sp} status graphs (Figure 6).

	Composite risk assessment		Graphical likelihood inference for fishery status (Table 1; Figure 6)	
Year	$P(C > C_{F\text{msy}})$	$P(C > C_{\text{sp}})$	LR for regions H_1 to H_5	LR for regions H_6 to H_{11}
1980	0.023	<0.001	1; 1.39; 5.72; >1,000; >1,000	1; 1.39; >1,000; >1,000; >1,000; >1,000
1985	<0.001	<0.001	2.08; 1; >1,000; >1,000; >1,000	2.08; 1; >1,000; >1,000; >1,000; >1,000
1990	0.041	0.003	3.19; 1; 8.17; >1,000; >1,000	3.22; 1; >1,000; >1,000; >1,000; >1,000
1995	0.042	<0.001	1.17; 1; 2.48; >1,000; >1,000	1.17; 1; >1,000; >1,000; >1,000; >1,000
2000	0.910	1.000	>1,000; 2.16; 1.68; 1; 17.64	>1,000; >1,000; 376; 1.68; 1; 14.73
2005	<0.001	0.002	9.68; 1; >1,000; >1,000; >1,000	9.68; 1; >1,000; >1,000; >1,000; >1,000

fishery status and, hence, management. The graphical approach provided estimates of fishery status consistent with those of the composite risk assessment method (Table 2). The likelihood ratios of the graphical approach quantified the strength of all possible descriptions of fishery status shown as graphical regions.

Discussion

The graphical approach used here to evaluate fishery status was based on a risk analysis that compares the difference between catch and $C_{F\text{msy}}$ or C_{sp}. This approach also included information on the population status as well as indications of uncertainty in the estimation of fishery status. For example, when population abundance is high, overexploitation may put the fishery status mainly in states H_4 and H_{10}, but when population abundance is low, overexploitation will tend to put the fishery status mainly in states H_3 and H_8. Thus, the implications of overexploitation for fishery status are very different depending on population abundance (Table 1).

This graphical depiction through the $C_{F\text{msy}}$ and C_{sp} spaces offers a powerful way to understand risk and uncertainty that can be interpreted by all participants in the management of a fishery. Although the approach is technically not easy, the output results are vivid, general, and straightforward. Thus, it is a valuable tool for communicating stock assessment results. Further detailed quantification, with more regions subdividing the graphical region, can be developed to better evaluate the risk by including more information on exploitation and stock abundance status.

The basis for the C_{sp} status graphs in Figure 2 is the comparison of the catch with the surplus production; therefore, the corresponding exploitation rate to reach the surplus production when abundance is lower than N_{msy} will be higher than F_{msy}. When abundance is higher than N_{msy}, the corresponding exploitation rate to reach the surplus production will be lower than F_{msy}. Due to the possibility of the Allee effect (Dennis 1989; Frank and Brickman 2000), caution should be exercised in using this approach to explain stock status when stock abundance is low. A combination of status graphs for $C_{F\text{msy}}$ and C_{sp} is suggested when explaining stock status.

For the graphical method described in this study, an approach similar to the surplus production model can be derived from an age-structured model that estimates F from the age-structured model and estimates F_{msy} from a combination of a yield-per-recruitment model and a stock–recruitment model derived from age-structured models (Shepherd 1982). Surplus production in year t can be estimated as $(N_{t+1} + C_t) - N_t$ (Quinn and Deriso 1999); the surplus production curve can be derived from a combination of a yield-per-recruitment model and a stock–recruitment model (Shepherd 1982), though the result may be different from yearly estimated surplus production. Because of the difficulty in solving multiparameter models when using the likelihood approach, algorithms such as the Markov chain Monte Carlo (MCMC) method, which is widely used for Bayesian statistics, can also be used to solve for likelihood estimation using objective priors. Examples can be found in Geyer and Thompson (1992) and Geyer (1994). In those studies, MCMC was used to obtain MLEs, and calculating the likelihood profile was simply a matter of maximizing over the nuisance parameter for each fixed value of the parameter of interest.

Uncertainty in fishery status should be included by managers in setting fishery management policy. Harvest strategies need to correspond to the different time frames as well as fishery status conditions. For example, if the best estimate shows that currently C is less than $C_{F\text{msy}}$, but the graphical approach shows that H_3 is within the LRCI of the current fishery status or that the likelihood ratio of H_3 is low, managers should adopt a precautionary management strategy even if a management policy based on F_{msy} is used. This is especially needed when the population size is low (i.e., the fishery is in the region of H_1, H_3, or H_5 or in the region of H_6, H_8, or H_9). With improved understanding of current fishery status, fishery managers would be able to make better decisions and better help other stakeholders understand and implement those decisions (Boucek et al. 2001).

In this study, we provided intervals and painted the regions of the status graphs based on the LRCI; we also provided likelihood ratios to address the strength of the different hypotheses about the fishery status shown as regions in the status graphs. The method is much more general than just the calculation of an LRCI with k equal to 6.82 or 20.0 and could be used for any limit reference point and any k-value. For a specific fishery, k-values may be chosen based on the characteristics of the fishery, the fishery status, and the risk level that the management agency and other stakeholders would like to accept. The k-values selected to paint the regions are set arbitrarily in this paper, but for real management scenarios k can be based on experience or on agreement among stakeholders. Royall (1997) suggested a k-value of 8 as strong evidence. The higher the k-value chosen, the more risk averse is the guidance for fishery status interpretation and management.

Using k to represent the evidence threshold, observed data can be considered evidence in favor of H_2 (if $[L_2/L_1] \geq k$), evidence in favor of H_1 (if $[L_2/L_1] \leq [1/k]$), and no evidence (if $[1/k] < [L_2/L_1] < k$). Choosing an appropriate k-value is analogous to choosing an appropriate significance level in frequentist hypothesis testing. Equivalent to the type I (α) and type II (β) errors used in frequentist statistics, the likelihood approach calculates the evidence of supporting the false hypothesis versus the evidence of supporting the true hypothesis. After k is chosen, we can calculate the probability of supporting the false hypothesis (e.g., H_2) over the true hypothesis (e.g., H_1) as

$$P(\text{misleading evidence}) = P[(L_2/L_1) \geq k],$$

and we can calculate the probability of failing to support H_2 when H_2 is in fact true as

$$P(\text{weak evidence}) = P[(L_2/L_1) < k].$$

In contrast to the frequentist paradigm, with the likelihood approach the error rates are independent of the measurements of evidence (Royall 1997).

Methods for dealing with uncertainty and risk in the state of a fishery include the use of decision tables (Hilborn and Walters 1992) and risk assessment (FAO 1995; Helser et al. 2001; Jiao et al. 2005). These analyses are based on (1) comparison of population biomass or abundance with a reference biomass or abundance or (2) comparison of an indicator reference point with the management reference point. Composite risk assessment assesses the probability that population size or harvest is larger than the corresponding biological reference point. Results from composite risk assessment help us to judge the fishery status. The graphical approach proposed in this paper gives comparable fishery status evaluation as the composite risk assessment method. It considers uncertainty in both the indicator reference points and the management reference points. However, the amount of information displayed by the composite risk assessment is not as thorough as in the likelihood inference approach provided here. The graphical likelihood inference approach evaluates the strength of the evidence in each possible fishery status. It shows the fishery status and its uncertainty over time vividly via graphical presentations, which are statistically valid and easy to understand by all parties involved in the fishery. The graphical approach is thus a valuable tool for communicating stock assessment results.

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References

Berger, J. O., and R. L. Wolpert. 1988. The likelihood principle, 2nd edition. Institute of Mathematical Statistics, Lecture Notes, Monograph Series, Volume 6, Beachwood, Ohio.

Boucek, M., R. Clemen, L. Maguire, and K. Reckhow. 2001. Stakeholder values and scientific modeling in the Neuse River watershed. Group Decision and Negotiation 10:355–373.

Bowman, A. W., and A. Azzalini. 1997. Applied smoothing techniques for data analysis. Oxford University Press, Oxford, UK.

Decker, D. J., and C. C. Krueger. 1993. Communication: catalyst for effective fisheries management. Pages 55–75 *in* C. C. Kohler and W. A. Hubert, editors. Inland fisheries management in North America. American Fisheries Society, Bethesda, Maryland.

Dennis, B. 1989. Allee effects, population growth, critical density, and the chance of extinction. Natural Resource Modeling 3:481–538.

Edwards, A. W. F. 1992. Likelihood. Johns Hopkins University Press, Baltimore, Maryland.

FAO (Food and Agriculture Organization of the United Nations). 1995. Precautionary approach to fisheries part 1: guidelines on the precautionary approach to capture fisheries and species introductions. FAO Fisheries Technical Paper 350/1.

Frank, K. T., and D. Brickman. 2000. Allee effects and compensatory population dynamics within a stock complex. Canadian Journal of Fisheries and Aquatic Sciences 57:513–517.

Geyer, C. J. 1994. On the convergence of Monte Carlo maximum likelihood calculations. Journal of the Royal Statistical Society Series B 56:261–274.

Geyer, C. J., and E. A. Thompson. 1992. Constrained Monte Carlo maximum likelihood for dependent data (with discussion). Journal of the Royal Statistical Society Series B 54:657–699.

Gimenez, O., R. Choquet, L. Lamor, P. Scofield, D. Fletcher, J. D. Lebreton, and R. Pradel. 2005. Efficient profile-likelihood confidence intervals for capture-recapture models. Journal of Agricultural, Biological, and Environmental Statistics 10:1–13.

Hatton, I. A. 2003. Graphical decision analysis of exploited fisheries. Master's thesis. McGill University, Montreal, Quebec.

Helser, T. E., A. Sharov, and D. M. Kahn. 2001. A stochastic decision-based approach to assessing the status of the Delaware Bay blue crab stock. Pages 63–82 *in* J. M. Berkson, L. L. Kline, and D. J. Orth, editors. Incorporating uncertainty into fishery models. American Fisheries Society, Symposium 27, Bethesda, Maryland.

Hilborn, R., and M. Mangel. 1997. The ecological detective: confronting models with data. Princeton University Press, Princeton, New Jersey.

Hilborn, R., and C. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics, and uncertainty. Chapman and Hall, New York.

Jiao, Y., and Y. Chen. 2004. An application of generalized linear models in production model and sequential population analysis. Fisheries Research 70:367–376.

Jiao, Y., Y. Chen, and J. Wroblewski. 2005. An application of the composite risk assessment method in assessing fisheries stock status. Fisheries Research 72:173–183.

Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, resource exploitation and conservation: lessons from history. Science 260:17–36.

May, R. M., J. R. Beddington, C. W. Clark, S. J. Holt, and R. M. Laws. 1979. Management of multispecies fisheries. Science 205:267–277.

Myers, R. A., and B. Worm. 2003. Rapid worldwide depletion of predatory fish communities. Nature (London) 423:280–283.

NRC (National Research Council). 1997. Improving fish stock assessments. National Academy Press, Washington, D.C.

Owen, A. 1990. Empirical likelihood ratio confidence regions. Annals of Statistics 18:90–120.

Polacheck, T., R. Hilborn, and A. E. Punt. 1993. Fitting surplus production models: comparing methods and measuring uncertainty. Canadian Journal of Fisheries and Aquatic Sciences 50:2597–2607.

Punt, A. E. 1988. Model selection for the dynamics of Southern African hake resources. Report Benguela Ecology Program of South Africa 15:395.

Quinn, T., and R. B. Deriso. 1999. Quantitative fish dynamics. Oxford University Press, Oxford, UK.

Restrepo, V. R., and J. E. Powers. 1999. Precautionary control rules in U.S. fisheries management: specification and performance. ICES Journal of Marine Science 56:846–852.

Restrepo, V. R., G. G. Thompson, P. M. Mace, W. L. Gabriel, L. L. Wow, A. D. MacCall, R. D. Methot, J. E. Powers, B. L. Taylor, P. R. Wade, and J. F. Witzig. 1998. Technical guidance on the use of precautionary approaches to implementing National Standard 1 of the Magnuson–Stevens Fishery Conservation and Management Act. NOAA Technical Memorandum NMFS-F/SPO-31.

Roughgarden, J., and F. Smith. 1996. Why fisheries collapse and what to do about it. Proceedings of the National Academy of Sciences of the United States of America 93:5078–5083.

Royall, R. 1997. Statistical evidence: a likelihood paradigm. Chapman and Hall, London.

SAFMC (South Atlantic Fishery Management Council). 2006. SEDAR stock assessment for large coastal sharks. SAFMC, Panama City, Florida.

Shepherd, J. G. 1982. A versatile new stock-recruitment relationship for fisheries, and the construction of sustainable yield curves. Journal du Conseil Conseil International pour l'Exploration de la Mer 40:67–75.

Starr, P., J. H. Annala, and R. Hilborn. 1998. Contested stock assessment: two case studies. Canadian Journal of Fisheries and Aquatic Sciences 55:529–537.

Taper, M. L., and R. S. Lele. 2004. The nature of scientific evidence. University of Chicago Press.

Thomas, D. R., and G. L. Grunkemeier. 1975. Confidence interval estimation for survival probabilities for censored data. Journal of the American Statistical Association 70:865–871.

Wade, P. R. 1999. A comparison of statistical methods for fitting population models to data. Pages 249–270 *in* G. W. Garner, S. C. Amstrup, J. L. Laake, B. F. J. Manly, L. L. McDonald, and D. G. Robertson, editors. Marine Mammal Survey and Assessment Methods. Balkema, Rotterdam, the Netherlands.

Walters, C., and J. Maguire. 1996. Lessons for stock assessment from the northern cod collapse. Reviews in Fish Biology and Fisheries 6:125–137.

Watson-Wright, W. 2007. The promise of an ecosystem approach: lessons from the past – hopes for the future. American Institute of Fisheries and Research Biologists, 50th Anniversary Symposium, Seattle.