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Original Article

Leveraging scientific uncertainty in fisheries management for estimating among-assessment variation in overfishing limits

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Fisheries management systems can utilize probability-based harvest control rules to incorporate scientific uncertainty and manager risk tolerance when setting catch limits. A precautionary buffer that scales with scientific uncertainty is used to calculate the acceptable biological catch from the overfishing limit (OFL) for US West Coast groundfish and coastal pelagic species. A previous analysis formed the basis for estimating scientific uncertainty as the among-assessment variation in estimates of historical spawning biomass time-series. This "historical biomass" approach may underestimate scientific uncertainty, because the OFL is a function of estimated exploitable biomass and fishing mortality. We developed a new approach that bases the calculation of scientific uncertainty on projected spawning biomass (SSB) and OFLs, accounting for uncertainty in recruitment and among-assessment variation. OFL projections yielded a higher estimate of uncertainty than SSB (0.502 vs. 0.413 for 25-year projections and 0.562 vs. 0.384 for a 1-year projection, assuming a deterministic stock-recruitment relationship). Assuming a stochastic stock-recruitment relationship produced smaller estimates of uncertainty (0.436, 25-year OFL projections; 0.452, 1-year OFL projections; 0.360, 25-year SSB projections; 0.318, 1-year SSB projections). The projection-based approach presented herein is applicable across stocks and regions that conduct assessments with sufficient and consistent outputs for calculating an OFL.

Keywords: catch limits, fisheries, harvest control rules, projection, scientific uncertainty.

Introduction

Fisheries science serves as a good example of managing natural resources and ecosystems at the intersection of participants' conservation, economic, traditional and recreational values. Managers and scientists are tasked with developing and implementing pragmatic management solutions to honour these values while navigating these "complex, unpredictable, and variable" socio-natural systems (Sethi, 2010). Identifying the risk associated with using marine resources is a high priority for stakeholders due to the perception that fisheries management has failed in the past, shifting public attitudes towards risk aversion, and improved computational resources (Francis and Shotton, 1997). Estimating the probability that management decisions result in overfishing depends on identifying and quantifying uncertainty (Edwards, 2016). The desire to evaluate the consequences of management strategies in the face of such uncertainty drives the development of fisheries stock assessment methodology (Punt and Hilborn, 1997).

To highlight the role that stock assessment plays in identifying the risk of overfishing, it is necessary to describe how uncertainty arises in the fisheries management process. Generally, fisheries management is a feedback loop of data collection, analysis (e.g. stock assessment), review, presentation of scientific advice, decision-making, and regulation implementation. First, it is necessary to acknowledge the process uncertainty inherent to all natural systems due to the underlying stochasticity in population dynamics, such as unpredictable variation in recruitment, growth, and natural mortality, and accept this as an irreducible and uncontrollable uncertainty (Edwards, 2016). Observation uncertainty, the variation in measurement of observable quantities such as catch or size-at-age is associated with data collection (Rosenberg and Restrepo, 1994). The analysis phase of fisheries management often leads to model uncertainty, the misspecification of model parameters or structure (e.g. assuming the incorrect form for selectivity as a function of size), and estimation uncertainty, the inaccuracy and imprecision in the estimated model parameters (Francis and Shotton, 1997). Process, observation, model, and estimation uncertainties are collectively referred to as scientific uncertainty, and methods for quantifying these within the stock assessment process are well represented across fisheries jurisdictions and taxa.

Fisheries managers and scientists can leverage uncertainty to design precautionary strategies that produce "risk-neutral" estimates of catch (Ralston *et al.*, 2011). These strategies can manifest as harvest control rules (HCRs), i.e. guidelines for determining the annual catch limit (ACL) for a fishery. Generally, application of an HCR in the United States is a multistep process: (i) a stock assessment calculates the overfishing limit (OFL) for a fishery; (ii) the acceptable biological catch (ABC) is set below the OFL to account for scientific uncertainty; and (iii) managers decide on an ACL that must be less than or equal to the ABC. The P^* method, a probability-based HCR, is a management strategy that determines the precautionary buffer that scales with scientific uncertainty to set management reference points (Prager *et al.*, 2003). The P^* HCR defines a distribution of the OFL centred on the assessment's OFL estimate, with a measure of variation defined by an estimate of scientific uncertainty (i.e. process, estimation, and model specification uncertainty). P^* itself is hence the percentile of the OFL distribution corresponding to the risk of overfishing considered tolerable by fisheries managers. US legislation under the Magnuson–Stevens Fishery Conservation and Management Act and National Standards mandates that P^* must never exceed 0.5, as doing so would lead to a risk-prone decision-making process (i.e. risk prone to overfishing; Federal Register, 2009). Catch limit implementation falls under the jurisdiction of the National Oceanic and Atmospheric Administration National Marine Fisheries Service, and the scientific components of the HCRs (the OFL distribution) are determined by the Scientific and Statistical Committees (SSCs), which are appointed by the eight US Regional Fisheries Management Councils.

There are several ways to quantify scientific uncertainty in stock assessments. These include estimating standard errors and confidence/credible intervals using asymptotic, likelihood profile, bootstrapping, and Bayesian methods. These methods are conditioned on the model of the population dynamics and the observation process being correct, although ensemble modelling is emerging as a way to capture some of the uncertainty due to choices in the modelling process (e.g. Brodziak and Walsh, 2013; Stewart and Hicks, 2018). Ralston *et al.* (2011) developed an approach for quantifying scientific uncertainty to serve as a proxy for the standard deviation of the OFL distribution used in the P^* HCR for US West Coast groundfish and coastal pelagic species stocks. This approach assumes that the OFL distribution can be characterized using a log-normal distribution for the historical biomass estimate in the terminal year with a mean of one and a standard error in log space. Ralston *et al.* (2011) used variation in time series of estimates of historical spawning biomass among multiple stock assessments for the same stock as a proxy for estimation and model specification uncertainty. This variation, for the most data-rich stocks, those with catch history, abundance indices, or biological data (e.g. length and/or age compositions), was quantified using the estimated coefficient of variation ($C.V.$) of the among-assessment variation in estimates of historical biomass based on 81 assessments of 15 groundfish and 2 coastal pelagic stocks. The SSC of the Pacific Fishery Management Council (PFMC) endorsed this approach for data-rich stocks and decided that the measure of scientific uncertainty should increase as data availability and assessment quality decrease for data-limited and data-poor stocks. In practice for the PFMC groundfish and coastal pelagic species tier system (locally referred to as categories), this is manifested as a minimum $C.V.$ of 0.36 for data-rich stocks (Category 1), double the (assumed) uncertainty for stocks in Category 2 ($C.V. = 0.72$), and four times the assumed uncertainty for Category 3 stocks ($C.V. = 1.44$; Ralston *et al.*, 2011).

This approach was a good first step in quantifying scientific uncertainty for use in the P^* HCR, but there remains the opportunity to improve the approach and further understand the errors in quantities most directly related to the setting of catch limits (i.e. the OFL). For example, using historical estimates of spawning stock biomass (SSB) to calculate among-assessment variation (hereby referenced as the *historical biomass approach*) assumes that the uncertainty in the OFL arises only from the uncertainty in terminal year biomass and this assumption can lead to negatively biased estimates of scientific uncertainty (Ralston *et al.*, 2011). In contrast, calculating among-assessment variation by quantifying how projections of OFLs (hereby known as the *projection-based approach*) vary among assessments of the same stocks is a direct measure of the management quantity of interest. Projections capture some of the uncertainty in the estimates of current stock abundance and age structure and how the abundance and age/size structure change over time. As noted by Shertzer *et al.* (2008), quantifying the variation in OFL projections may also capture some of the uncertainty associated with assumptions about the fishing mortality rate (for US fisheries, F_{MSY} or a proxy thereof).

This study outlines a projection-based approach for estimating the scientific uncertainty (i.e. the standard error of the log-OFL distribution) used in the P^* HCR. We investigate how projections of OFLs vary (i) among assessments of the same stock, (ii) among assessments across stocks (i.e. when pooling stocks), (iii) across multiple projection start years, and (iv) when assuming deterministic and stochastic recruitment dynamics. Further analyses include replicating the historical biomass approach with the addition of new assessments completed after 2011 (i.e. the year the original Ralston *et al.* analysis was completed) and projecting spawning biomass in addition to OFLs.

Material and methods

Sources of uncertainty

Variation in estimates of OFLs and spawning biomass among multiple assessments of the same stocks can arise from several sources: (i) chosen model structure, (ii) fixed parameter values and prior distribution selection for other parameters, (iii) data availability, (iv) the members of the stock assessment team conducting the assessment, (v) the composition of the group established to review the assessment, and (vi) the type and version of the software that was used (Ralston *et al.*, 2011).

Scientific uncertainty is associated with each step of calculating an OFL: (i) estimating the current exploitable biomass and (ii) projecting biomass for a pre-specified number of years while applying an estimate of (or proxy for) F_{MSY} to the forecasts of future biomass (Ralston *et al.*, 2011). The historical biomass approach uses spawning biomass and does not directly use the above biomass inputs for determining an OFL, while the projection-based approach developed in this work directly projects exploitable biomass and applies the assumed F_{MSY} proxy to calculate an OFL.

Data utilized

The US West Coast groundfish and coastal pelagic species stock assessments were chosen for investigating the projection-based approach to ensure comparability with the historical biomass approach (Supplementary Table S1). These assessments were used in the historical biomass approach because they exhibited variability in estimates of historical biomass among multiple stock assessments for the same stocks (Figure 2 of Ralston *et al.*, 2011). Assessments completed in Stock Synthesis (Methot and Wetzel, 2013) after 2007 (v. 3.03a or later) were used in the projection-based approach because they provided the necessary quantities required for projecting spawning biomass and OFLs (Supplementary Table S2).

Not all assessments reported spawning biomass, but a common metric was needed to compare spawning biomass. Spawning output (usually in number of eggs) based on the non-proportional egg-to-weight relationship described by Dick (2009) was reported in the recent assessments of bocaccio and darkblotched rockfish. Comparing variation across multiple assessments for these stocks required the units of spawning output to be converted into spawning biomass. Thus, spawning biomass in metric tons was calculated for assessments with spawning output reported in eggs:

$$\mathrm{SSB}_y = \sum_{a}^{A} W_{s,a} N_{y,s,a}, \tag{1}$$

where SB_y is the spawning biomass in year y, a is the age, A is the age plus group, s is the sex (i.e. female), $W_{a,s}$ is mature female weight-at-age, and $N_{y,s,a}$ is the female numbers-at-age. Mature female weight-at-age was calculated as follows:

$$W_{s,a} = \sum_{l} W_l m_l \rho_{a,l}, \tag{2}$$

where W_l is the female weight-at-length, m_l is the female proportion mature-at-length, and $\rho_{a,l}$ is the proportion of females of age a in length class l.

Projecting OFLs and spawning biomass

Overview

The projection-based approach directly quantifies the variation in projections of OFL and spawning biomass across the following dimensions: (i) among assessments of the same stock, (ii) among assessments across multiple stocks, (iii) across multiple projection start years, and (iv) when assuming deterministic vs. stochastic recruitment. Projections were based on the best estimates of biomass, age structure, biological parameters, and selectivity from the stock assessment, and these estimates change over time. Thus, to further characterize uncertainty, projections were started from two sets of multiple historical years (i.e. 1998, 2003, and 2008 and 1994–2008). The 1998, 2003, and 2008 historical start years were projected 25 years (e.g. 1998–2023) and the 1994–2008 start years were projected 1 year into the future (e.g. 1994–1995).

1998, 2003, and 2008 were selected as projection start years to cover a range of alternatives that are not too close together in time, although a different set could have been selected. 2008 was the last projection start year because some stocks (i.e. canary rockfish and lingcod) had two assessments in recent versions of Stock Synthesis, limiting the analysis to only benchmark assessments conducted from 2009 forward. The choice of 25 years is somewhat arbitrary, but the projections of spawning biomass and OFL largely reach equilibrium by this time. In principle, the projection length could be selected to reflect how long assessment results would be used for. Specifically, the 1-year projections starting in a range of start years were undertaken to mimic the time scale of tactical fisheries management. Assuming a deterministic stock–recruitment relationship does not directly capture projection uncertainty; thus, we also conduct stochastic projections based on a stock–recruitment relationship with log-recruitment deviations with bias correction.

Seven US West Coast groundfish stocks have 18 assessments completed in a version of Stock Synthesis that provides the required quantities for the projection-based approach (Supplementary Table S2). These quantities were extracted for each projection start year in the two sets of multiple historical years (i.e. 1998, 2003, and 2008 and 1994–2008) from each of the available assessments and served as inputs for the population dynamics model (Figure 1A). The population dynamics model was used to project OFL and spawning biomass either 25 years or 1 year into the future while assuming a deterministic or stochastic ($N = 100$) stock–recruitment relationship (Figure 1B). We tested the following two approaches to projecting stochastic stock–recruitment: (i) only considering uncertainty in future recruitment and (ii) accounting for uncertainty in past and future recruitment and ultimately used the latter [i.e. (ii)] for analysis. This process is repeated for the remaining projection start years in the two sets of multiple historical years (i.e. 1998, 2003, and 2008 and 1994–2008). The resulting assessment model outputs were analysed using the set of models in Tables 1 and 2 to calculate the σ_{SSB} and σ_{OFL} values based on among-assessment variation (Figure 1C). The stochastic model runs allowed us to quantify σ_{SSB} and σ_{OFL} based on within-assessment variation as well (see equations in Table 3).

Population dynamics

OFLs were computed by applying a target fishing rate, F_{target} (US West Coast groundfish: $F_{50\%}$ for rockfish, $F_{45\%}$ for roundfish, and $F_{30\%}$ for flatfish) to estimates of current exploitable biomass. F_{target} is the target harvest rate that results in an expected decline in spawning biomass-per-recruit equal to 50% (for rockfish), 45% (for roundfish), or 30% (for flatfish) (PFMC, 2014). F_{target} served as the proxy for F_{MSY}.

The estimated natural mortality and projected fishing mortality for the time series covered in the assessment were used to calculate total mortality, Z for projections:

$$Z_{s,a} = M_{s,a} + F_{\mathrm{target}} \sum_{\mathrm{f}} S_{s,a,\mathrm{f}} \psi_{\mathrm{f}}, \tag{3}$$

where a is the age, s is the sex, and f is the fleet. S is the selectivity by age, sex, and fleet and ψ_{f} is the relative fishing mortality rate by fleet f, both at the end of the year before the projections start. Z was then used to project the numbers-at-age by sex forward using the following standard age-structured model:

$$\begin{aligned} N_{y+1,s,a} &= N_{y,s,a-1} e^{-Z_{s,a-1}} && \text{if } 1 \le a < A \\ N_{y+1,s,A} &= N_{y,s,A-1} e^{-Z_{s,A-1}} + N_{y,s,A} e^{-Z_{s,A}} && \text{if } a = A \end{aligned} \tag{4}$$

where N is the numbers-at-age by year and sex, and A is the plus group. The numbers-at-age for the first year of projection period were set to the estimates from the Stock Synthesis assessment.

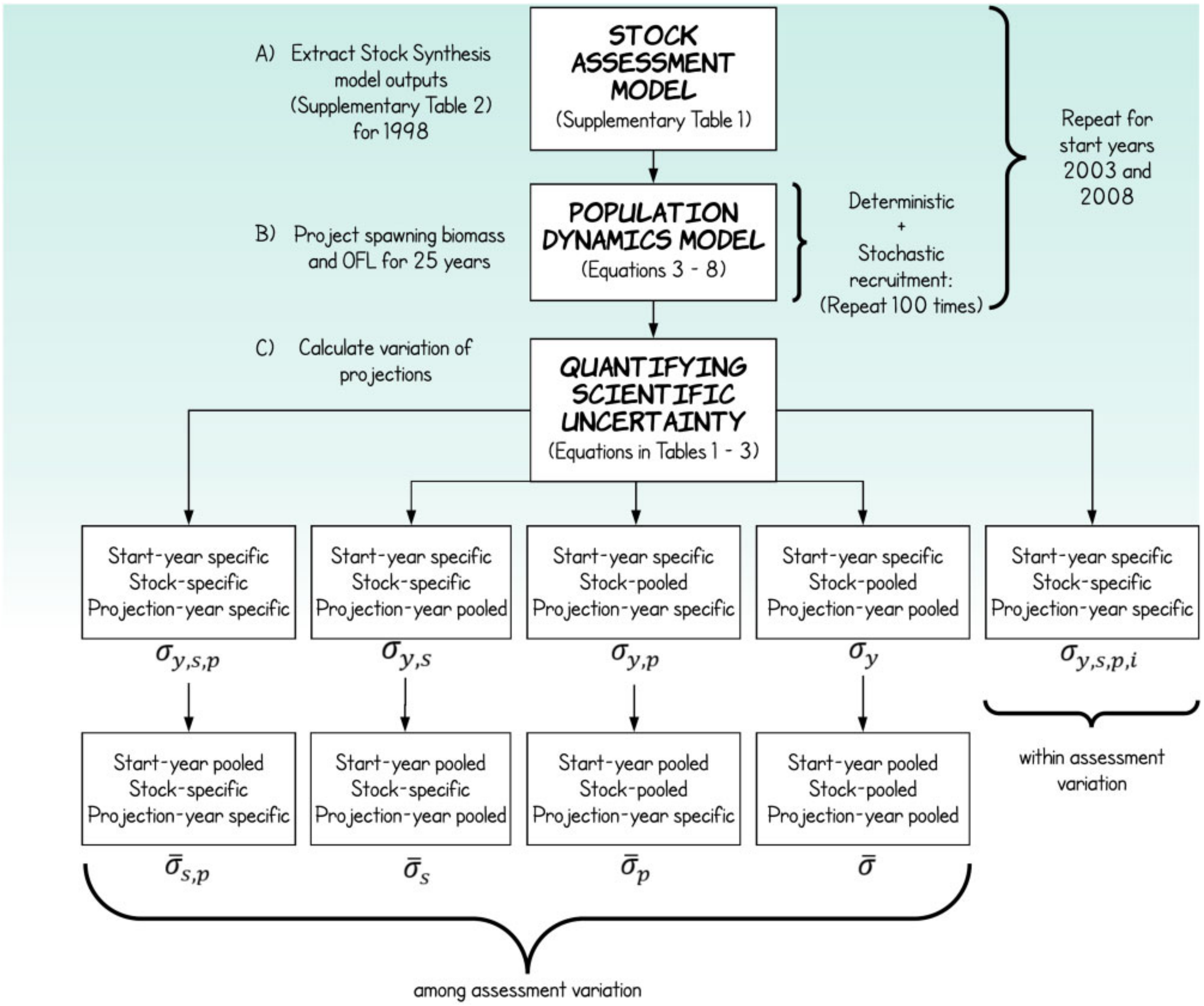

Figure 1. A conceptual overview of the projection-based approach using the projection start years of 1998, 2003, and 2008 as an example.

The projected numbers-at-age were converted to SSB using (1).

The projected numbers of fish at Age 0 were calculated using the Beverton–Holt stock–recruitment relationship because this relationship formed the basis for the original assessments, and log-recruitment deviations with bias correction were added for stochastic projections:

$$N_{y,s,a=0} = \frac{4hR_0\mathrm{SSB}/\mathrm{SSB}_0}{(1-h)+(5h-1)(\mathrm{SSB}/\mathrm{SSB}_0)}, \qquad (6)$$

$$N_{y,s,a=0} = \frac{4hR_0\mathrm{SSB}/\mathrm{SSB}_0}{(1-h)+(5h-1)(\mathrm{SSB}/\mathrm{SSB}_0)} e^{\varepsilon_y-\sigma_r{}^2/2}, \qquad (7)$$

where R_0 is the unfished recruitment, h is the steepness parameter, σ_r is the standard deviation (in log space) of recruitment, SSB_0 is the unfished SSB, and $e^{\varepsilon_y-\sigma_r{}^2/2}$ are recruitment multipliers with bias correction. The unfished SSB was computed using numbers-at-age and fecundity at unfished equilibrium. The assumption of log-normality was made for consistency with how recruitment is modelled in the original assessments.

The effects of recruitment variation will not immediately manifest in spawning biomass or OFL because several of the stocks are fairly long-lived (e.g. middle panels of Figures 2 and 3). To better capture uncertainty in the first projection years, Equation (7) was also used to generate recruitment estimates for some of the cohorts that constitute the projection start year, with the extent of variation defined by the asymptotic standard errors for the annual recruitment deviations from the last 10 years of the assessment (the asymptotic standard errors for recruitment are close to zero for most assessments for recruitments that occurs 11 or more years before the end of the assessment period). The generated recruitment values are then projected to the start year given the values of Z-at-age estimated in the assessment.

OFLs by year were calculated as follows:

$$\mathrm{OFL}_y = F_{\mathrm{target}} \sum_{s}\sum_{f}\sum_{a} W_{s,f,a} S_{s,f,a} \psi_f \frac{N_{y,s,a}(1-e^{-Z_{s,a}})}{Z_{s,a}}, \qquad (8)$$

where W is the weight-at-age accounting for length-specific fishery selectivity, sex, and fleet for the end of the year before the projections start.

Table 1. Equations for the projection-based approach, where *s* is the stock, *y* is the projection year, *p* is the projection start year (measured since the start year), and *i* is an individual assessment.

Among-assessment estimate	Deterministic stock–recruitment relationship	Stochastic stock–recruitment relationship	Equation number
Stock-, projection year-, and start year-specific mean	$\overline{\ln[X_{s,p}]}_y = \frac{1}{n_{s,p}}\sum_i \ln[X_{s,p,i}]_y$	$\overline{\ln[X_{s,p}]}_y = \frac{1}{100n_{s,p}}\sum_j\sum_i \ln[X_{s,p,i,j}]$	T1.1
Projection year pooled, stock pooled, and start year specific	$\sigma_y = \sqrt{\frac{1}{\sum_s\sum_p (n_{s,p}-1)}\sum_s\sum_p\sum_i \left(\ln[X_{s,p,i}]_y - \overline{\ln[X_{s,p}]}_y\right)^2}$	$\sigma_y = \sqrt{\frac{1}{\sum_s\sum_p (100n_{s,p}-1)}\sum_s\sum_j\sum_i \left(\ln[X_{s,p,i,j}]_y - \overline{\ln[X_{s,p}]}_y\right)^2}$	T1.2a
Projection year pooled, stock specific, and start year specific	$\sigma_{y,s} = \sqrt{\frac{1}{\sum_p (n_{s,p}-1)}\sum_p\sum_i \left(\ln[X_{s,p,i}]_y - \overline{\ln[X_{s,p}]}_y\right)^2}$	$\sigma_{y,s} = \sqrt{\frac{1}{\sum_p (100n_{s,p}-1)}\sum_s\sum_j\sum_i \left(\ln[X_{s,p,i,j}]_y - \overline{\ln[X_{s,p}]}_y\right)^2}$	T1.2b
Projection year specific, stock pooled, and start year specific	$\sigma_{y,p} = \sqrt{\frac{1}{\sum_s (n_{s,p}-1)}\sum_s\sum_i \left(\ln[X_{s,p,i}]_y - \overline{\ln[X_{s,p}]}_y\right)^2}$	$\sigma_{y,p} = \sqrt{\frac{1}{\sum_s (100n_{s,p}-1)}\sum_s\sum_j\sum_i \left(\ln[X_{s,p,i,j}]_y - \overline{\ln[X_{s,p}]}_y\right)^2}$	T1.2c
Projection year specific, stock specific, and start year specific	$\sigma_{y,s,p} = \sqrt{\frac{1}{n_{s,p}-1}\sum_i \left(\ln[X_{s,p,i}]_y - \overline{\ln[X_{s,p}]}_y\right)^2}$	$\sigma_{y,s,p} = \sqrt{\frac{1}{100n_{s,p}-1}\sum_j\sum_i \left(\ln[X_{s,p,i,j}]_y - \overline{\ln[X_{s,p}]}_y\right)^2}$	T1.2d

$X_{s,p,i}$ are the estimates of OFL or spawning biomass for year $p+y+1$ based on assessment *i* starting in year *y*, $n_{s,p}$ is the total number of projection values across all assessments for stocks *s* in projection year *p*, and *j* represents the projection replicate under stochastic recruitment. These equations were used when calculating for both σ_{SSB} and σ_{OFL}.

Table 2. Equations for summarizing the estimates of σ_{SSB} and σ_{OFL} pooled over projection start years, where N_{start} is the number of projection start years (i.e. 3 for 1998, 2003, and 2008 and 15 for 1994–2008).

Among-assessment estimate	Equation	Equation number
Projection year-pooled and stock-pooled mean	$\overline{\sigma} = \sqrt{\frac{1}{N_{\mathrm{start}}}\sum_y \sigma_y^2}$	T2.1a
Projection year-pooled and stock-specific mean	$\overline{\sigma_s} = \sqrt{\frac{1}{N_{\mathrm{start}}}\sum_y \sigma_{y,s}^2}$	T2.1b
Projection year-specific and stock-pooled mean	$\overline{\sigma_p} = \sqrt{\frac{1}{N_{\mathrm{start}}}\sum_y \sigma_{y,p}^2}$	T2.1c
Projection year-specific and stock-specific mean	$\overline{\sigma_{s,p}} = \sqrt{\frac{1}{N_{\mathrm{start}}}\sum_y \sigma_{y,s,p}^2}$	T2.1d

The projections were undertaken using code developed in R (R Core Team, 2019).

Quantifying uncertainty in projections

Scientific uncertainty (σ) is approximated using among-assessment variation estimated as the log-scale standard error obtained from: (i) the historical biomass approach (σ_{HB}); (ii) the projection-based approach for spawning biomass (σ_{SSB}); and (iii) the projection-based approach for OFL (σ_{OFL}). The log-space uncertainty assumption [Method 2 of three tested by Ralston *et al.* (2011)] was selected as the preferred method for calculating uncertainty by the PFMC SSC during the review of the historical biomass approach and was adopted for use in this study. We assumed that the σ_{HB}, σ_{SSB}, and σ_{OFL} estimates among stocks and years are independent and calculated approximate (likely negatively biased) 95% confidence intervals based on the chi-squared distribution. The projection-based approach calculated σ_{SSB} and σ_{OFL} while accounting for the following four dimensions: projection year, stock [year and stocks were treated as a sampling unit by Ralston *et al.* (2011)], projection start year, and the replicate trajectories of spawning biomass and OFL due to sampling of future (and past) recruitment deviations (stochastic projections only). Point estimates of σ_{SSB} and σ_{OFL} were pooled over these dimensions to characterize the corresponding contribution to scientific uncertainty (see Tables 1–3 for equations). The σ_{SSB} and σ_{OFL} representing among-assessment variation were summarized over eight combinations of dimensions each, and within-assessment variation was represented by one combination of dimensions each (i.e. start year, species, projection year, and assessment; Figure 1C). Four of the among-assessment variation statistics are start year specific (i.e. 1998, 2003, 2008, or 1994–2008) and alternate as follows: (i) stock specific and projection year specific, (ii) stock specific and pooled over projection years, (iii) pooled over stocks and projection year specific, and (iv) pooled over stocks and projection years. The remaining four are pooled over start year for the same combinations of specific and pooled stocks and projection years.

Historical biomass approach

Since Ralston *et al.* (2011), 14 of the 17 groundfish and coastal pelagic stocks used to inform among-assessment variation estimated using the historical biomass approach have new assessments (Supplementary Table S1). We estimated σ_{HB} based on historical biomass again with these new assessments included. New (i.e. since

Table 3. Equations for calculating within-assessment variability for σ_{SSB} and σ_{OFL}, where j indicates a stochastic projection and $[X_{s,p,i,j}]_y$ are the stochastic projection estimates by stock, projection year, assessment, stochastic replicate, and start year.

Within-assessment estimate	Stochastic stock–recruitment relationship	Equation number
Stock-, projection year-, and start year-specific mean	$\overline{\ln[X_{s,p,i}]_y} = \frac{1}{100}\sum_j \ln[X_{s,p,i,j}]_y$	T3.1
Projection year pooled, start year, stock, and assessment specific	$\sigma_{y,s,i} = \sqrt{\frac{1}{\sum_p (100-1)}\sum_j\sum_p\left(\ln[X_{s,p,i,j}]_y - \overline{\ln[X_{s,p,i}]_y}\right)^2}$	T3.2a
Projection and start year, stock, and assessment specific	$\sigma_{y,s,p,i} = \sqrt{\frac{1}{100-1}\sum_j\left(\ln[X_{s,p,i,j}]_y - \overline{\ln[X_{s,p,i}]_y}\right)^2}$	T3.2b

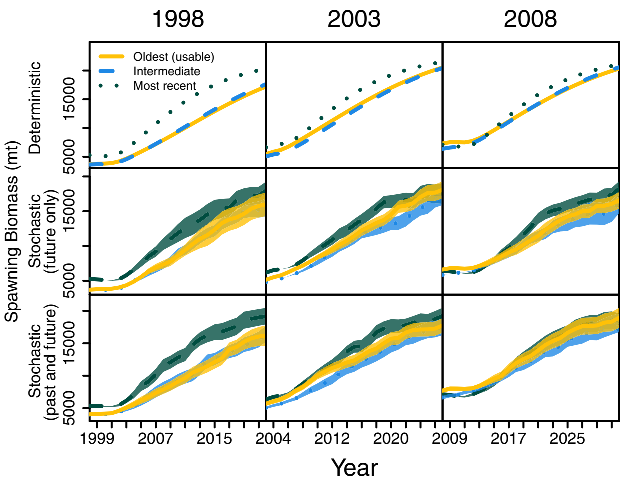

Figure 2. Spawning biomass trajectories for bocaccio based on three start years (1998, 2003, and 2008; columns) and three stock assessments (conducted in 2009, 2011, and 2015; yellow solid lines, blue dashed lines, and green dotted lines). Results are shown in the upper panels for the deterministic projections, in the center panels for stochastic projections that only consider uncertainty in future recruitment, and in the lower panels for stochastic projections that account for uncertainty in past and future recruitment.

2009) assessments for Pacific whiting were not included because the management structure for the hake fishery changed with the implementation of an international treaty. Cabezon, chilipepper, and yellowtail rockfishes have not been assessed since 2009 and are also not included in this update (i.e. the information for 13 of the 17 original stocks was updated for use in this study). For comparison to the projection-based approach proposed in this paper, the Ralston *et al.* (2011) approach was also applied to: (i) the original 17 stocks, updated with any assessments conducted since 2009 (Supplementary Table S1); (ii) the seven stocks included in the projection-based approach using all available assessments; and (iii) the seven stocks based on only the assessments used in the projection-based approach. The updated stock-specific estimate of σ_{HB} was based on Method 2 of Ralston *et al.* (2011), i.e.:

$$\sigma_{\mathrm{HB}} = \sqrt{\frac{1}{\sum_t (n_t - 1)}\sum_t\sum_i\left(\ln[\mathrm{SSB}_{i,t}] - \overline{\ln[\mathrm{SSB}_t]}\right)^2}, \qquad (9)$$

where SSB_t is the SSB by year, n_t is the number of available assessments for year t ($n_t > 2$), and i is the individual assessment.

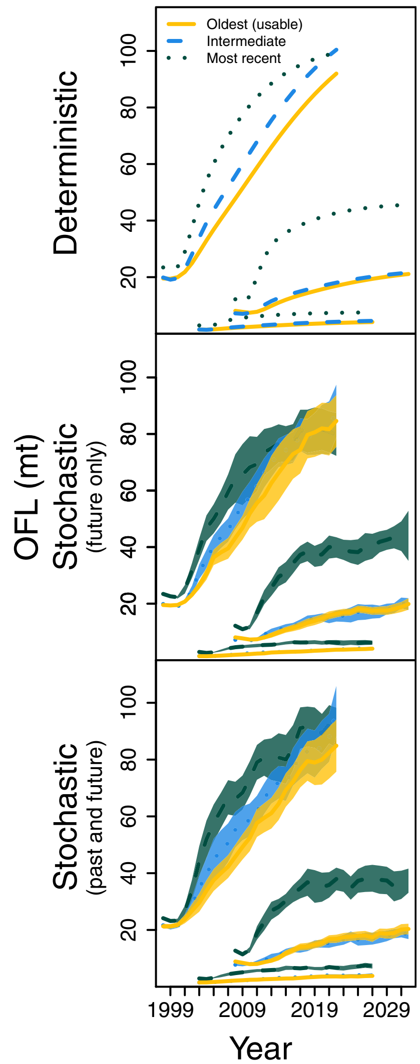

Figure 3. As for Figure 2, except the results pertain to the OFL. The OFL trajectories for the three start years (1998, 2003, and 2008) are combined into a single plot for each recruitment type to demonstrate the difference in the scale of OFL.

Results

Estimates of σ based on projections

The results for a single stock, bocaccio (i.e. stock specific), are described before presenting results for how OFL projections vary

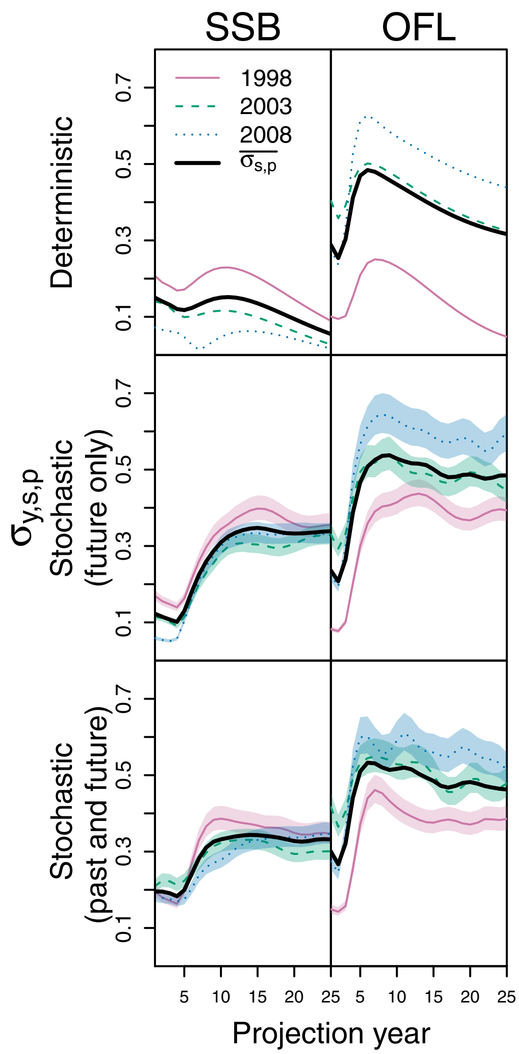

Figure 4. Values of σ for bocaccio based on spawning biomass (σ_{SSB}; left column) and OFL (σ_{OFL}; right column). Results are shown in the upper panel for the deterministic projections, in the center panel for stochastic projections that only consider uncertainty in future recruitment, and in the lower panel for stochastic projections that account for uncertainty in past and future recruitment, by start year and pooled over start-years. The shaded regions in the lower panel indicate 95% confidence intervals (no 95% confidence intervals are shown in the upper panel owning to small sample size). The solid black line represents the projection year-specific, stocks-pooled mean (Equation T2.1d).

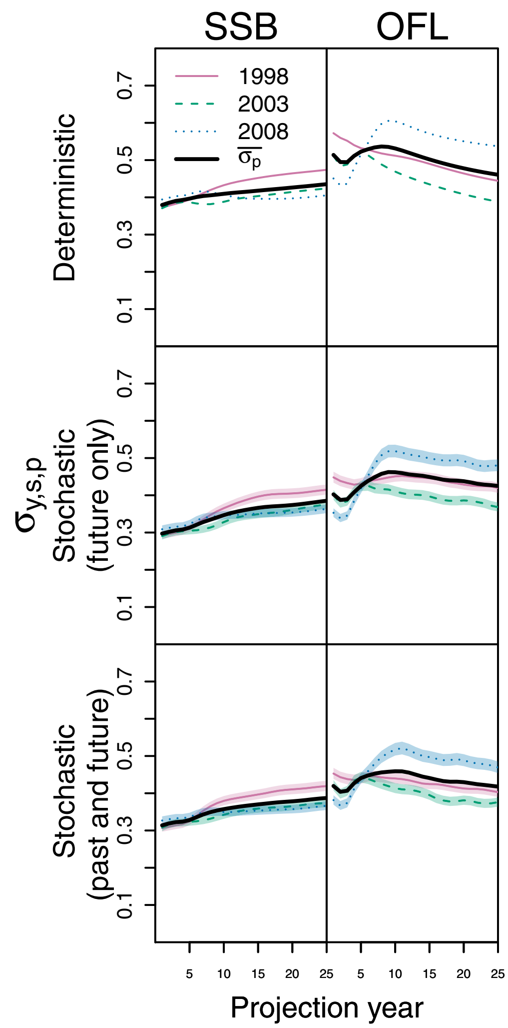

Figure 5. Values of σ aggregated over stocks based on spawning biomass (σ_{SSB}; left column) and OFL (σ_{OFL}; right column). Results are shown in the upper panel for the deterministic projections, in the center panel for stochastic projections that only consider uncertainty in future recruitment, and in the lower panel for stochastic projections that account for uncertainty in past and future recruitment, by start year and pooled over start-years. The shaded regions in the lower panel indicate 95% confidence intervals (no 95% confidence intervals are shown in the upper panel owning to small sample size). The solid black line represents the projection year-specific, stocks-pooled mean (Equation T2.1c).

among assessments across stocks (i.e. stock pooled). OFL and spawning biomass projections were conducted for bocaccio based on three start years (1998, 2003, and 2008) and three assessments (conducted in 2009, 2011, and 2015; columns of Figure 2 represent start year, and the lines represent the assessments). The OFL and spawning biomass trajectories for the remaining six stocks are provided in Supplementary Figures S1–S12. Multiple assessments for the same stock are identified as "Oldest (available)", "Intermediate A", "Intermediate B", and "Most Recent" (e.g. for bocaccio, oldest corresponds to the assessment conducted in 2009, Intermediate A corresponds to that conducted in 2011, and Most Recent corresponds to that conducted in 2015; Figures 2 and 3). Intermediate A and B differentiate when a single stock has more than three assessments (e.g. darkblotched rockfish in Supplementary Figure S3; see Supplementary Table S1 for the years in which assessments were conducted for all stocks). Accounting for uncertainty throughout the projection period was best achieved by the assumption of stochasticity in past and future recruitment (the third rows of Figures 2 and 3 vs. the second rows, which only consider uncertainty in future recruitment). Thus, values of σ_{SSB} and σ_{OFL} (columns on Figure 2 and panels of Figure 3) were calculated from projections assuming either a deterministic stock–recruitment relationship or stochastic stock–recruitment relationship (rows of Figure 4; see Supplementary Figures S13–S15 for the remaining stocks). The among-assessment variation for all seven stocks was pooled, and the OFL projections yielded higher variation than spawning biomass (Figure 5).

Estimates of within-assessment variation were calculated based on the stochastic OFL and spawning biomass projections that account for past as well as future stochasticity (Figure 6; see Supplementary Figures S16–S21 for the remaining stocks).

The variability in future spawning biomass and OFL is sensitive to differences among assessments in key assumptions (e.g. values of parameters, such as initial recruitment size and stock–recruitment steepness; Supplementary Table S3). The stock-specific variation in spawning biomass was smaller when including stochastic recruitment for the canary rockfish, lingcod, Pacific ocean perch, and widow rockfish for the 1998, 2003, and 2008 projection start years (Table 4; start year-specific values presented in Supplementary Table S4a). The variation in future OFL was smaller for stochastic recruitment for canary rockfish, darkblotched rockfish, lingcod, and Pacific ocean perch (Table 4; start year-specific values presented in Supplementary Table S4b). However, the variation in OFL was smaller for all seven stocks when conducting 1-year stochastic projections for start years 1994–2008 (Table 4 and Figure 7; start year-specific deterministic values presented in Supplementary Tables S5 and S7; start

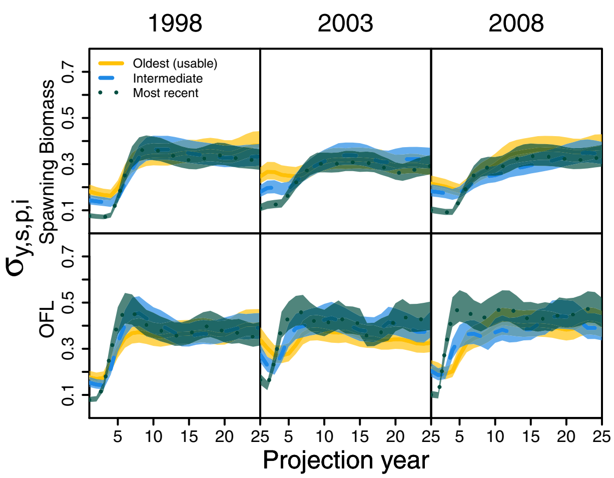

Figure 6. Values of within-assessment σ for bocaccio based on spawning biomass (σ_{SSB}) and OFL (σ_{OFL}). Results are shown for stochastic analyses, that account for uncertainty in past and future recruitment, by start year and assessment (i.e. 2009, 2011, and 2015). The shaded regions indicate 95% confidence intervals.

year-specific stochastic values presented in Supplementary Tables S6 and S8). The stock-pooled estimates of variation for future spawning biomass and OFL were greater for a deterministic stock–recruitment (i.e. 0.413 vs. 0.360 for spawning biomass and 0.502 vs. 0.436 for OFL) for the 1998, 2003, and 2008 projection start years (Table 5). Increasing the number of projection start years (i.e. 1994–2008) yielded the same pattern with a stock-pooled σ_{OFL} of 0.562 for deterministic recruitment and 0.452 for stochastic recruitment (Table 5).

Updating σ_{HB} based on the historical biomass approach

Consistent with Ralston *et al.* (2011), the groundfish and coastal pelagic species stock assessments used in the update of the σ_{HB} based on the historical biomass approach were data-rich stocks with multiple benchmark assessments (15 groundfish and two pelagic stocks; Supplementary Figure S22). "Update" assessments, where data are simply refreshed without model parameterization and specification review, were not included in the analyses. The number of benchmark assessments per stock used for this meta-analysis ranged from 3 (chilipepper rockfish and cabezon) to 23 (Pacific whiting; Supplementary Table S9).

Stock-specific results

The number of benchmark stock assessments and differences in model assumptions influence the biomass trajectories and distribution of residuals for the 17 stocks (Supplementary Figures S22 and S23). These distributions are bimodal for stocks that have few assessments, which may differ in model assumptions and result in trajectories of spawning biomass that do not overlap (e.g. shortspine thornyhead, and yelloweye rockfish). For most other stocks, the residual distributions appear unimodal. Some distributions exhibit long tails (e.g. yellowtail rockfish and petrale sole). Darkblotched rockfish and widow rockfish have more uniform distributions than the original analysis of Ralston *et al.* (2011) following the addition of recent stock assessments. The log-scale standard deviations range from 0.154 (cabezon) to 0.994 (shortspine thornyhead), with an average of 0.403 (Supplementary Table S9).

Stock-pooled results

The distributions of residuals were pooled by life history groupings and by all stocks (Supplementary Figure S24A). The

Table 4. The start year- and projection year-pooled values of σ_{SSB} and σ_{OFL} for each stock using the projection-based approach.

	Spawning biomass, σ_{SSB}		**OFL, σ_{OFL}**			
Pooled start years	**1998, 2003, 2008**		**1998, 2003, 2008**		**1994–2008**	
Recruitment	**Deterministic**	**Stochastic**	**Deterministic**	**Stochastic**	**Deterministic**	**Stochastic**
Stocks	$\overline{\sigma_s}$	$\overline{\sigma_s}$	$\overline{\sigma_s}$	$\overline{\sigma_s}$	$\overline{\sigma_s}$	$\overline{\sigma_s}$
Bocaccio	0.123	0.305	0.388	0.472	0.327	0.314
Canary rockfish	0.544	0.427	0.815	0.562	1.185	0.820
Darkblotched rockfish	0.180	0.226	0.523	0.484	0.507	0.463
Lingcod	0.214	0.187	0.720	0.526	0.751	0.536
Petrale sole	0.130	0.134	0.104	0.131	0.135	0.117
Pacific ocean perch	0.854	0.583	0.382	0.358	0.389	0.316
Widow rockfish	0.575	0.481	0.395	0.530	0.419	0.357

Twenty-five-year projections were conducted from each of the 1998, 2003, and 2008 start years, and 1-year projections were undertaken for the 1994–2008 start years.

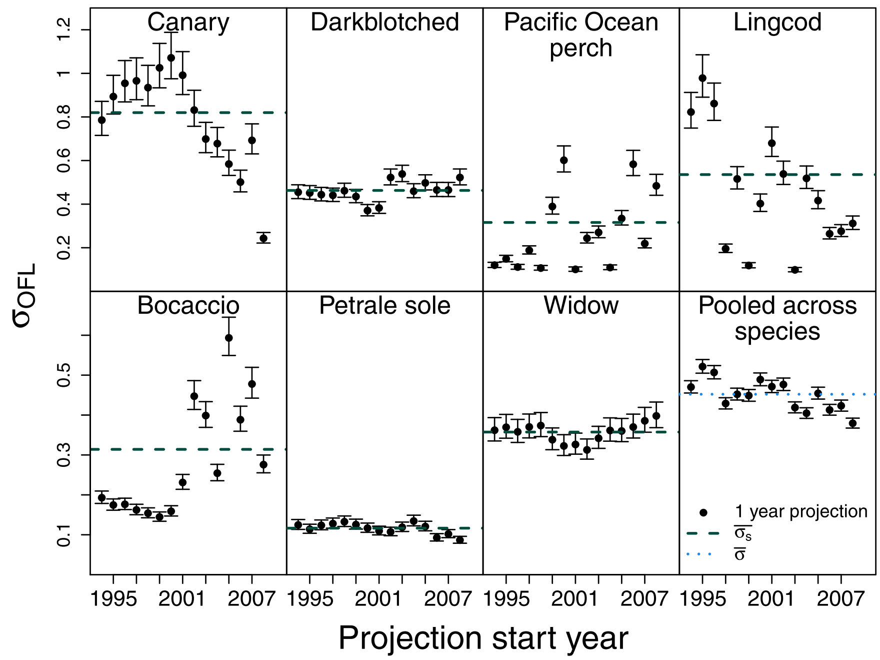

Figure 7. Stock- and projection start year-specific estimates of σ_{OFL} based on stochastic projections with uncertainty in past and future recruitment, and 1-year projections of OFL (N = 100). The green dashed lines are the stock-specific pooled historical start year estimates of σ_{OFL}. The lower right panel is the retrospective start year-specific estimates of σ_{OFL} pooled across stocks. The dotted blue line indicates the stock-pooled and start year-pooled estimate of σ_{OFL}.

Table 5. Comparison of start year-, projection year-, and stock-pooled values from the projection-based approach to the values calculated from using the historical biomass approach.

	$\bar{\sigma}$			
Analysis	**Deterministic**	**Stochastic**	**Number of stocks**	**Number of assessments**
Projection-based approach				
25-Projection years	1998, 2003, 2008			
Spawning biomass, σ_{SSB}	0.413	0.360	7	18
OFL, σ_{OFL}	0.502	0.436	7	18
1-Projection year	1994–2008			
Spawning biomass, σ_{SSB}	0.384	0.318	7	18
OFL, σ_{OFL}	0.562	0.452	7	18
Historical biomass approach				
Ralston et al. (2011)				
Assessments before 2009	0.358		17	81
Updated with recent assessments				
All available assessments, σ_{HB}	0.403		17	110
All available assessments, σ_{HB}	0.349		7	43
Assessments after 2009 only, σ_{HB}	0.286		7	18

N_{stock} indicates the number of stocks used in each analysis, and N_a indicates the number of assessments. The final two rows of the historical biomass approach values were determined using the same seven stocks used in the projection-based approach. Note that the historical biomass approach does not involve a start year assumption or whether future recruitment is deterministic or stochastic.

distributions are close to normal for all groupings, whereas in the Ralston *et al.* (2011) analysis, roundfish, flatfish, and coastal pelagic stocks exhibited some non-normal features (Figure 3 of Ralston *et al.*, 2011). The pooled σ_{HB} point estimates from this update, the accompanying approximate 95% confidence intervals, and the original pooled point estimates from Ralston *et al.* (2011) are reported in Supplementary Table S9. Pooling the deviations across all stocks (Supplementary Figure S24B) leads to a point estimate of $\sigma_{HB} = 0.403$ with an approximate 95% confidence interval based on the chi-squared distribution of $0.387 \leq \sigma_{HB} \leq 0.421$ (Table 5).

Sensitivities

The historical biomass approach for updating σ_{HB} was repeated with the subset of stocks that were used in the projection-based approach (i.e. bocaccio, canary rockfish, darkblotched rockfish, lingcod, petrale sole, Pacific ocean perch, and widow rockfish; Supplementary Figures S25 and S26). The stock-specific variation is shown in Supplementary Table S11. This analysis yielded a pooled σ_{HB} point estimate of 0.349, with an approximate 95% confidence interval of $0.328 \leq \sigma_{HB} \leq 0.373$ when all available assessments were included [i.e. those included in Ralston *et al.* (2011) as well as the new assessments completed post-2009; Table 5]. The σ_{HB} point estimate was 0.286 with an approximate 95% confidence interval of $0.265 \leq \sigma_{HB} \leq 0.311$ when only assessments used in the projection-based approach (i.e. only assessments complete post-2009) were analysed using the historical biomass approach (Table 5).

Discussion

Our findings confirm Ralston *et al.*'s (2011) assertion that accounting only for uncertainty in terminal year historical biomass leads to an underestimate of the measure of scientific uncertainty. Specifically, the value of σ_{HB} would be 0.403 based on the updated analyses of this article compared with 0.358 by Ralston *et al.* (2011). Both these values are substantially lower than the stock-pooled estimates of σ_{OFL} based on OFL projections (e.g. 0.562 and 0.452 for stochastic and deterministic 1-year projections for the 1994–2008 start years, respectively). The projection-based approach could only be applied to a subset of stocks, but the estimate of σ_{HB}, using the historical biomass approach, for the subset of stocks used for the projection-based approach is lower ($\sigma_{HB} = 0.403$ if all assessments are included and $\sigma_{HB} = 0.286$ if only the assessments used in the projection-based approach are included) than for the entire set of available stocks (i.e. the updated historical biomass approach value of $\sigma_{HB} = 0.403$), suggesting that the higher value for σ_{SSB} for the projection-based approach is not a consequence of the choice of stocks.

The projection-based approach captures more sources of uncertainty than the historical biomass approach. Notably, the former accounts for forecast error, which compounds over time, as well as the difference in variance between projecting spawning biomass and projecting OFLs, with the latter being consequential. Nevertheless, the projection-based method requires some additional specifications, specifically the length of the projection period and the number of start years considered. While the former could be linked to the expected time between assessments, the latter is more a balance among more projection results, the lack of independence among results for long projections based on start years that are close in time, and computational limitations.

Accounting for the uncertainty in recruitment, both in the past and in the future, makes the calculations more complete but does not qualitatively change the results; in fact, in several cases, the value for among-assessment variation was lower when account was taken of stochastic recruitment. The uncertainty estimates based on spawning biomass and OFL projections are nevertheless still likely underestimates owing, for example, to the assumption that quantities such as growth, natural mortality, and the steepness of the stock–recruitment relationship remain constant into the future. There is evidence for several stocks that these parameters are not stationary (Punt *et al.*, 2014; Forrest *et al.*, 2018; Lee *et al.*, 2018).

It was not possible to apply the projection-based approach to as many stocks as the historical biomass approach. This is because the detailed information needed (e.g. Supplementary Table S2) to conduct projections for several of the assessments for which historical biomass trajectories are reported in tables and figures of assessment documents is no longer available due to changes in how assessments are archived for the US West Coast. In addition, assessments based on a different model structure could not be easily compared because of the need to update software to allow projections to be undertaken. This is not a major concern for the US West Coast groundfish fishery or other regions where assessments use predominantly the same software (e.g. Stock Synthesis or C++ Algorithmic Stock Assessment Laboratory (CASAL); Bull *et al.*, 2005; Doonan *et al.*, 2016). This concern could be consequential for regions, such as Australia, where assessments are often based on bespoke models (Dichmont *et al.*, 2016), and the US North Pacific, where several assessment software packages (including Stock Synthesis and Assessment Method from Alaska (AMAK), Anon, 2015) are used. However, Australia has applied the historical biomass approach to its southeastern stocks (Punt *et al.*, 2018), and applying the projection-based approach could be implemented for these stocks in this region. The US North Pacific has a set of default projections, and the projection-based approach could be a standard addition to these practices.

Quantifying scientific uncertainty is critical for the determination of catch limits if a probability-based HCR is adopted. For the US West Coast, the P^* HCR has been adopted and it was considered for adoption for crab stocks in the US North Pacific region (Punt *et al.*, 2012). However, the implementation of the P^* approach (and whether it is used at all) differs regionally within the United States. Specifically, the level of scientific uncertainty that determines the OFL buffer varies based on the management plans that utilize the P^* HCR and the corresponding peer-review body (the SSC). The SSCs for the US Fishery Management Councils employ various methods for estimating the extent of scientific uncertainty in accordance with the corresponding fishery management plans. Generally, the most data-rich stocks use the estimated OFL distribution from the stock assessment and the Council's risk tolerance (i.e. a specific P^*) to calculate the buffer from the OFL to the ABC. Alternative methods, e.g. bootstrapping and Markov Chain Monte Carlo (MCMC) simulations [Gulf of Mexico Fishery Management Council (GMFMC), 2011], MCMC yield-per-recruit analyses (New England Fishery Management Council, 2010), and Bayesian simulation approaches (North Pacific Fishery Management Council ; Punt *et al.*, 2012), have been identified as viable candidates for stock assessments that do not produce OFL estimates with uncertainty. Bootstrapping or Bayesian methods could be combined with the projection-based method so that uncertainty in, for example, the population numbers-at-age in the first year of the projection period, was accounted for. Similarly, uncertainty in biological parameters, such as natural mortality and growth, and hence the value of the F_{MSY} proxy could be accounted for were this uncertainty quantified. However, there are at present no estimates of uncertainty for stock assessments of US West Coast groundfish stocks based on bootstrapping and Bayesian methods.

The historical biomass approach assumes among-assessment variation in historical biomass is a proxy for the scientific uncertainty associated with OFLs. Quantifying the uncertainty in projections of OFLs as shown here directly captures the impact of more of the uncertainty associated with assessment model assumptions, estimates of current stock abundance and age structure, how these estimates change over time, and estimates of the proxies for the fishing mortality rate (F_{MSY} or proxy thereof). The value of σ_{HB} from the historical biomass approach of 0.286 (i.e. based on using only the assessments completed after 2009, $N = 7$) is lower for the assessments used in the projection-based OFL approach ($\sigma_{OFL} = 0.562$ or $\sigma_{OFL} = 0.452$ with or without accounting for recruitment stochasticity). This supports that using variation in historical biomass as a proxy for variation in OFL may underestimate uncertainty. The projection-based OFL approach was presented to, reviewed and adopted by the PFMC SSC for defining the OFL distribution for the P^* HCR in the US west coast groundfish and coastal pelagic stocks fisheries (PFMC, 2019a). The PFMC SSC used the value of σ_{OFL} from the 1-year projections with the 1994–2008 start years (i.e. 0.452) and applied an adjustment to account for the use of only seven stocks (vs. the 17 used in the original historical biomass approach analysis), by applying the ratio of the 2017 updated value of $\sigma_{HB} = 0.403$ and the sensitivity estimate value of $\sigma_{HB} = 0.349$ (i.e. calculated using the same seven stocks used in the projection-based approach). The resulting value of 0.521 was rounded to 0.500 and established for Category 1 stocks (PFMC, 2019b). For future applications of the projection-based approach, we recommend multiple projection start years with projection periods that mirror the tactical management period for setting the ABC.

The projection-based OFL approach addresses additional uncertainty related to changes in assessment model assumptions about, and estimates of, natural mortality and productivity, selectivity, and relative year class abundance. However, there are opportunities to extend the approach. For example, it would be useful to know the extent to which variation in key parameters, such as growth, natural mortality, and productivity within assessments each contribute to the overall uncertainty. The projection-based approach currently only includes assessments that had a relatively simple structure (e.g. no seasonal structure) and several older assessments had to be ignored because it is no longer possible to conduct projections for them. If projection-based approaches are to be standard, we recommend that the assessment (whether conducted in Stock Synthesis or not) provides projections from various start values routinely, which will allow projections based on multiple assessment types to be included in the calculation of among-assessment variation, thereby capturing yet another source of uncertainty.

Adoption of a buffer between the OFL and the ABC is paramount to the precautionary approach to fisheries management if overfishing is to be avoided. The historical biomass approach of Ralston *et al.* (2011) provided an objective way to quantify the uncertainty on which the buffer could be based. The projection-based approach of this article is a better way to define σ and hence more appropriately define uncertainty. It requires only the results of projections that are commonly conducted for assessments and can hence be applied in a wide range of jurisdictions, which will also enhance consistency in how uncertainty is quantified among regions and stocks.

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Author contributions

KMP-J and AEP developed the conceptual framework. KMP-J collated the data and conducted the analyses. KMP-J and AEP drafted the article.

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