An Approach to Quantifying Scientific
Uncertainty in West Coast Stock Assessments

Groundfish & CPS Subcommittees
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Summary

Quantifying scientific uncertainty in estimating an appropriate catch level for a fish stock is challenging. Multiple sources of error can easily be identified, including measurement error that is conditioned on the adopted model, model specification error, forecast error, and uncertainty about overall stock productivity. In addition, there are without doubt other unknown factors that will negatively influence the precision of scientific advice on catch levels. Notwithstanding these difficulties, the Magnuson-Stevens Reauthorization Act (MSRA) identifies the quantification of scientific uncertainty in the development of advice on catch levels as a key requirement of the new law. Moreover, the Scientific and Statistical Committees (SSCs) of the Regional Fishery Management Councils have been given the responsibility to quantify that uncertainty.

While many sources of uncertainty exist, the focus here is on quantification of statistical measurement error and model specification error, particularly the latter. While not all inclusive, the study of these two factors is feasible with the information that is currently available. They are also likely to include the dominant sources of scientific uncertainty in the development of scientific advice vis-à-vis groundfish and coastal pelagic species catch levels at the Pacific Fishery Management Council.

Although full Bayesian integration through MCMC calculations is a preferred method of estimating measurement error “within” a stock assessment, an inadequate number of studies have successfully achieved that type of analysis. Consequently, we report the first order approximate estimates of the standard error on terminal biomass from stock assessments that are calculated by inversion of the model’s Hessian matrix (i.e., the asymptotic standard error). To summarize variation “among” stock assessments, as a proxy for model specification error, we characterize retrospective variation among multiple assessments of the same stock.

Results show that for 16 groundfish and coastal pelagic species (thornyhead excluded) the mean of the coefficient of variation on terminal biomass is 0.19 (s.d. = 0.09). This represents the average amount of statistical measurement error within assessments conducted for the PFMC. In contrast, the average coefficient of variation ascribable to model specification error (i.e., among assessment variation) is 0.51 (s.d. = 0.19), which is the far greater of the two sources of uncertainty. Given these results, if only among assessment variation is considered, and the probability of overfishing is fixed at 0.40, an appropriate buffer on the overfishing catch level is to reduce the harvest by ~12%.
Introduction

The Pacific Fishery Management Council currently manages a wide variety of west coast fish stocks under four different Fishery Management Plans (FMPs), including groundfish, coastal pelagic species (CPS), salmon, and highly migratory species (HMS). In the case of groundfish, the PFMC adopts optimum yields (OYs) for the fishery on a biennial basis following application of a harvest control rule to the results of stock assessments. Functionally, this procedure involves four separate calculations: (1) estimation of exploitable biomass in the current year, (2) projecting the population forward for several years into the near future, (3) applying a harvest rate to the projected population that would be expected to produce Maximum Sustainable Yield (MSY) in the long term, and (4) adjusting the projected catch downwards to account for a variety of factors of particular concern to management. Application of the MSY harvest rate ($F_{MSY}$ or its proxy) to the projected stock biomass results in an estimated Allowable Biological Catch (ABC), which has been considered an upper bound on annual catches, i.e., catches in excess of the ABC represent “overfishing.” Adjustment of the ABC catch downwards to account for the concerns of management then results in an OY. An example of such an adjustment is the 40:10 groundfish harvest control rule that reduces OY relative to the ABC once the biomass of a stock drops below 40% of its unfished level. Hence, under the Council’s traditional approach to setting groundfish catch levels, the ABC is the absolute upper limit on annual catch, whereas the OY incurs some reduction in catch to account for a variety of conservation concerns to management. A comparable procedure is in place for CPS, except that the OY is termed a harvest guideline (HG).

The Magnuson-Stevens Fishery Conservation and Management Act was re-authorized in 2008 and included new National provisions for the establishment of Annual Catch Limits (ACLs) to insure that chronic overfishing is prevented. An annual catch limit represents a numerically specified upper limit on the total mortality experienced by a stock that should not be exceeded. In addition, the Magnuson-Stevens Reauthorization Act (MSRA) stipulated that the Scientific and Statistical Committees (SSCs) of each of the eight regional Fishery Management Councils are now required to account for scientific uncertainty in the provision of management advice to their respective Councils. This new requirement effectively adds a new step in setting catch levels. In particular, the application of $F_{MSY}$ (or its proxy) to the projected biomass values from a stock assessment now results in an Overfishing Limit (OFL), which is identical to the old definition of the ABC. As before, annual catches in excess of the OFL constitute overfishing. However, under the new law the ABC is now defined as an annual catch amount that is reduced from the OFL in order to account for scientific uncertainty in the development of management advice by SSCs to their Councils. The expectation under MSRA is that scientific advice that is relatively uncertain will result in ABCs that are relatively lower, all other things being equal, i.e., a precautionary reduction with occur due purely to scientific uncertainty. The new law also requires that the ACL cannot exceed the newly defined ABC, but it will often be less than the ABC in order to account for non-scientific management uncertainties and/or concerns. Moreover, if management is unable to insure that annual catches remain below the ACL, possibly due to inadequate monitoring of shoreside landings during the fishing year, the law provides for the
establishment of an Annual Catch Target (ACT) below the ACL to insure that the ACL is not exceeded more than once in four years. The relationships of these various terms are depicted graphically in Figure 1 below.

Given the new requirement that each SSC is now responsible for characterizing scientific uncertainty in a manner that allows establishment of a precautionary “buffer” between the OFL and the ABC, this document summarizes the Pacific Fishery Management Council SSC’s preliminary approach to addressing this problem for groundfish and CPS stocks.

Sources of Uncertainty

As described previously, estimation of the OFL (formerly ABC) involves three basic steps: (1) estimation of current exploitable biomass \( B_t \), (2) projecting the current exploitable biomass into the future for several years \( B_{t+1}, B_{t+2}, \text{ etc.} \), and (3) applying an estimate of F\(_{\text{MSY}}\) to predictions of future biomass. While there are clear uncertainties associated with each step, the PFMC SSC elected to focus its attention first and foremost on variation in the estimation of current biomass in the terminal year of groundfish and CPS stock assessments. Our reason for doing so is aptly illustrated in Figure 2, which shows the results of 15 different Pacific whiting stock assessments that have been conducted for the PFMC over the last 18 years. It is instructive to consider this species because it is likely the most data-rich stock managed by the Council, it is of tremendous economic importance, and it has been assessed on an annual basis for many years. However, in spite of considerable resources having been devoted to evaluating the status of the stock, from an assessment retrospective perspective, estimates of biomass have
been highly variable. Note, for example, that estimated spawning biomass in 1985 has ranged from 1.2-5.9×10^6 mt; approximately a 5-fold range in abundance.

Reasons for these variations in stock size estimation are multitude, including differences in: (1) the modeling software that was used, (2) the composition of the analytical team doing the assessment, (3) the review panel composition, (4) changes in the availability of data, (5) altered parameter priors, and (6) overall model structure. Importantly, these issues contribute to variation in all groundfish and CPS stock assessments, which collectively demonstrate considerable “among” assessment variance. Hence, it is currently the view of the SSC that quantifying and accounting for this source of uncertainty is the first and most important to consider when establishing a buffer between the OFL and the ABC. However, as this process develops into the next biennial management cycle the SSC intends to consider other types of errors, including forecast uncertainty (Shertzer et al. 2008) and optimal harvest rate uncertainty (e.g., Dorn 2002; Punt et al. 2008). Hence, quantification of variation as revealed in this exercise should be considered a lower bound on total uncertainty at this time. However, even if forecast and harvest rate uncertainty were incorporated explicitly in this analysis, numerous other unaccounted for factors exist that may never be fully evaluated, including for example the effects of climate and/or ecosystem interactions on the estimation of an ABC.

Quantifying Biomass Uncertainty

For our analysis we consider two types of uncertainty in biomass estimation. The first is termed “within” assessment variability and is represented by the coefficient of variation (CV) on the terminal year biomass taken from the most recent stock assessment that has been conducted, whether it was a full or update assessment. In a very limited number of studies (e.g., Pacific Ocean perch) full Bayesian integration of uncertainty via Monte Carlo Markov Chain (MCMC) analysis has been achieved. However, such instances are
the exception. Consequently, we use the asymptotic standard error estimate on terminal biomass developed by inversion of the model’s Hessian matrix, i.e., the so-called Delta Method (Seber 1973) approximate estimate of variance. This error estimate can be considered a measure of statistical uncertainty “within” a stock assessment model that is “conditioned” or depends on all of the structural assumptions embedded within the model. We converted the asymptotic standard error to a CV by simple division using the terminal biomass statistic as the denominator.

However, as previously noted, “among” assessment variations are attributable to a wide variety of factors, many of which represent a significant form of model or structural uncertainty. Assertion of asymptotic or dome-shaped selectivity patterns is one example, as is incorporation of age-dependent natural mortality. Such structural issues will frequently change from one assessment to the next as. Likewise, biologically important fixed parameters often change from one assessment to the next (e.g., natural mortality or spawner-recruit productivity) and whole new data time series can be incorporated into the assessment model (e.g., the NWFSC combined trawl survey). Beyond such changes in model specification, among assessment variation includes other sources of variability due to, for example, differences in the reviewers who evaluated and approved an assessment.

To quantify total, among assessment, variability we assembled time series of biomass from historical assessments of a stock. Because of constraints on how much they could change, we excluded update assessments unless they were the most recent assessment conducted. In situations where a change in biomass metric across assessments occurred (e.g., mid-year biomass in one assessment and beginning year biomass in another) we used ratio estimation (Cochran 1977) over a common time frame to standardize to a common metric across all assessments that were conducted on a stock. Lastly, we limited the number of data points under consideration to the last 20 years from each assessment in order to focus our attention on variation associated with the estimation of current year biomass.

Biomass variation between two stock assessments was quantified by forming ratios of estimated abundances in common years. Specifically, if there existed an estimate of biomass \( B_t \) in common year \( t \) from assessments \( i \) and \( j \), we calculated: \( R_{ij,t} = \frac{B_{i,t}}{B_{j,t}} \), i.e., the proportional deviation of assessment \( i \) using assessment \( j \) as a standard. Based on a symmetry argument we also calculated \( R_{ji,t} \). Therefore, in any particular year, if there were \( n \) assessments with biomass estimates available, the total number of ratios that could be formed was equal to the number of permutations of \( n \) objects taken two at a time, which is \( n!/(n-2)! \).

All of the \( R_{ij,t} \) ratios so obtained were loge-transformed and the standard deviation of the data calculated. For each stock a frequency histogram of the log-ratios was plotted. Note that because \( \ln(R_{ij,t}) = -\ln(R_{ji,t}) \) all of the distributions were perfectly symmetrical. We used the estimated standard deviation of the \( \ln(R_{ij,t}) \) as a quantitative measure of among assessment variability.
To combine “within” and “among” sources of variation we note that for lognormally distributed random variables, the CV on the arithmetic scale is equal to \((\exp[\sigma^2]-1)^{0.5}\) (Johnson and Kotz 1970), where \(\sigma^2\) is the variance on the logarithmic scale. We used this relationship to convert the within assessment CV to a variance term on the logarithmic scale, added the square of the among assessment log-scale standard deviation, and back-transformed the total variance to a coefficient of variation on the arithmetic scale.

**Stock-Specific Accounts**

In the accounts that follow information for 15 groundfish and 2 CPS stocks is summarized. Specifically, we include the following well-studied, relatively data-rich species: bocaccio, canary rockfish, chilipepper, darkblotched rockfish, Pacific Ocean perch, shortspine thornyhead, widow rockfish, yelloweye rockfish, yellowtail rockfish, cabezon, lingcod, Pacific whiting, sablefish, Dover sole, petrale sole, Pacific mackerel, and Pacific sardine. All have been assessed using some version of the Stock Synthesis modeling program in a fully dynamic context.

The summary for each stock includes a brief description of the species, references to what assessments were included in the analysis, whether any ratio estimation was required to standardize biomass metrics, and plots showing: (a) time series of abundance from 1970 to the present, with the most recent assessment in bold, and (b) frequency histograms of the \(\ln(R_{ij,t})\).

**Bocaccio (Sebastes paucispinis):**

Bocaccio is an overfished rockfish that is currently under rebuilding (Figure 3). It is principally distributed in the State of California. We identified five stock assessments that could be incorporated into the meta-analysis (Ralston et al. 1996; MacCall et al. 1999; MacCall 2002; MacCall 2003; Field et al. In press). While earlier assessments of this species have been conducted, they did not identify a base model and instead presented a range of alternatives predicated on a predefined array of possibilities. Results from Field et al. (In press) were presented as mid-year total biomass, where as the four earlier studies referenced biomass at the beginning of the year. However, results from MacCall (2003) included time series in both biomass metrics and ratio estimation over the period 1951-2002 from that assessment was used to standardize to biomass at the beginning of the year \((\sum \text{begin-year biomass} / \sum \text{mid-year biomass} = 1.044)\). For bocaccio the standard deviation (\(\sigma\)) of the log-ratios is 0.554 (n = 292).

**Canary rockfish (Sebastes pinniger)**

Canary rockfish is also an overfished stock under a highly restrictive rebuilding plan (Figure 4). It is distributed along the entire U.S. west coast and is largely responsible for the implementation of the Rockfish Conservation Area (RCA) spatial trawl area closures. For the meta-analysis we report the results of eight stock assessments (Sampson and Stewart 1994; Sampson 1996; Williams et al. 1999; Crone et al. 1999; Methot and Piner 2002; Methot and Stewart 2005; Stewart 2008; Stewart 2009). All report their results in
Figure 3. Bocaccio time series of abundance (upper panel) and variation in abundance (lower panel).

Figure 4. Canary rockfish time series of abundance (upper panel) and variation in abundance (lower panel).
terms of spawning biomass [mt]. However, we made the following adjustments to the abundance time series from these assessments: (1) we averaged “base-1” and “base-2” models from Sampson and Stewart (1994), Sampson (1996) and Crone et al. (1999), (2) we added the southern results of Williams et al. (1999) to the northern results of Crone et al. (1999) to obtain a coastwide estimate, (3) we used a ratio estimate developed from the period 1967-93 based on the coastwide biomass from the combined 1999 assessments relative to the north (×1.16) to expand the northern results of Sampson and Stewart (1994) and Sampson (1996) to coastwide values, and (4) we averaged the “diff” and “no-diff” models from Methot and Stewart (2005). Following these adjustments we calculate that for canary rockfish $\sigma = 0.48$ based on 528 ratio estimates.

Chilipepper (Sebastes goodei)

Only two stock assessments of chilipepper were incorporated into this study (Ralston et al. 1998; Field 2008). This species is currently underutilized because landings have been constrained by restrictions that have been placed on the bocaccio fishery, a species with which it regularly co-occurs. Chilipepper is predominately found only in California. Because estimates of total age 1+ biomass were available from both assessments (Figure 5), no adjustments to the abundance time series were required. We calculate that $\sigma = 0.59$ based on the variation of 42 log-ratio estimates.

Darkblotched rockfish (Sebastes crameri)

This species is primarily distributed off the State of Oregon and is one of several overfished rockfish stocks that are currently under rebuilding (Figure 6). A review of past assessments indicates that full stock assessments were conducted in 2003 and 2005 and an update assessment was completed in 2009 (Rogers 2003; Rogers 2005; Wallace and Hamel In press). All three report time series of total age-1+ biomass and summarize the stock over the same geographical area. Consequently, no standardization of biomass metrics was required. Analysis of the log-ratio data 92 points yields a standard deviation of 0.18.

Pacific Ocean perch (Sebastes alutus)

Like the preceding species, Pacific Ocean perch (a.k.a. POP) is a northerly distributed overfished rockfish stock (Figure 7). Large removals occurred due to distant water foreign fishing fleets in the 1960s and POP was one of the first stocks of conservation concern to the PFMC. Based on an examination of material in previous PFMC Stock Assessment and Fishery Evaluation (SAFE) documents it was determined that only the assessments conducted in 1992, 1998, and 2009 (an update) could be included in this analysis (Ianelli et al. 1992; Ianelli and Zimmerman 1998; Hamel 2009). All of these studies provided time series of stock size in terms of total biomass. A summarization of the data yielded 48 ratio estimates and resulted in $\sigma = 0.52$. 
Figure 5. Chilipepper time series of abundance (upper panel) and variation in abundance (lower panel).

Figure 6. Darkblotched rockfish time series of abundance (upper panel) and variation in abundance (lower panel).
Shortspine thornyhead (*Sebastolobus alascanus*)

Shortspine thornyhead is a member of the “DTS” complex (Dover sole, thornyhead, and sablefish) and is harvested primarily in the continental slope trawl fishery (Figure 8). Like rockfishes, it is a member of the scorpionfish family, although it has quite different life history characteristics (e.g., oviparity). For this study three stock assessments were identified for detailed analysis (Ianelli *et al.* 1994; Piner and Methot 2001; Hamel 2005); no standardization of time series was required. Results show that the standard deviation of the 76 calculated log-ratio values was 1.50. Due to the markedly different biomass time series the distribution of $\ln(R_{ij,t})$ values was tri-modal and had very high variance.

Widow rockfish (*Sebastes entomelas*)

This species is another overfished rockfish that is under rebuilding (Figure 9). Five assessments met the necessary criteria for inclusion in the meta-analysis, including Ralston *et al.* (1997), Williams *et al.* (2000), He *et al.* (2003), He *et al.* (2006), and He *et al.* (In press). All studies reported total spawning output, although the data presented in Ralston *et al.* (1997) scaled differently relative to the other assessments. Hence, a ratio estimate was developed to convert spawning output from that study to be equivalent to the others. To accomplish the standardization the ratio of the sums of spawning output (SO) over the period 1970-97 was utilized, i.e., $(\sum \text{SO 2000 model}) / (\sum \text{SO 1997 model}) = 0.083$. Following standardization the 284 log-ratio data points resulted in $\sigma = 0.38$. 

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**Figure 7.** Pacific Ocean perch time series of abundance (upper panel) and variation in abundance (lower panel).
Figure 8. Shortspine thornyhead time series of abundance (upper panel) and variation in abundance (lower panel).

Figure 9. Widow rockfish time series of abundance (upper panel) and variation in abundance (lower panel).
Yelloweye rockfish (*Sebastes ruberrimus*)

This is yet another overfished rockfish stock that is found along the entire US west coast, typically in rockfish shelf habitats. Six assessments have been completed since 2001 (Figure 10), although two were updates and could not be utilized. The remaining four studies were evaluated here, i.e., Wallace 2001; Methot *et al.* 2002; Wallace *et al.* 2006; Stewart *et al.* In press. Results obtained from the most recent study (Stewart *et al.* In press) presented stock size in terms of larval production, whereas the three earlier studies used spawning biomass. The former statistic was therefore converted to units of spawning biomass by ratio estimation over the period 1924-2006. Specifically, results in Wallace *et al.* (2006) showed that \( \frac{\sum \text{spawning biomass}}{\sum \text{total biomass}} = 0.429 \), which when multiplied by the total biomass estimates provided in Stewart *et al.* (In press) yielded estimates of spawning biomass. After standardization of the time series the standard deviation of the 158 log-ratio estimates resulted in \( \sigma = 0.80 \).

Yellowtail rockfish (*Sebastes flavidus*)

This more northerly species, like chilipepper, has been underutilized in recent years due to constraints placed on it by concerns over other overfished rockfish, including canary and widow rockfish (Figure 11). Six assessments were identified that could inform the estimation of scientific uncertainty in stock size estimation (Tagart 1991; Tagart 1993; Tagart and Wallace 1996; Tagart *et al.* 1997; Tagart *et al.* 2000; Wallace and Lai 2005). All stocks reported the abundance of yellowtail rockfish in terms of total age-4+ biomass, which was summed over three sub-regions. However, the first four assessments each presented two alternative models, which were simply averaged for this analysis. This produced 456 log-ratio estimates, resulting in a standard deviation of 0.31.

Cabezon (*Scorpaenichthys marmoratus*)

Cabezon is a member of the sculpin family (Cottidae) that inhabits shallow, high relief reef systems in California and Oregon (Figure 12). Three stock assessments have been completed on the stock and were evaluated as part of the meta-analysis (Cope *et al.* 2004; Cope and Punt 2006; Cope and Key In press). The first assessment of cabezon did not report spawning output in the same units as the last two studies. A ratio estimate of the 1970-2003 summed spawning outputs from 2006 and 2004 assessments was therefore used to standardize the 2004 data (2006 units = \( 1.06 \times 10^{-3} \) \times 2004 units). After standardizing the data, 96 log-ratio estimates were calculated, yielding \( \sigma = 0.30 \).

Lingcod (*Ophiodon elongatus*)

Lingcod is a large hexagrammid west coast species of considerable importance to both commercial and recreational fisheries. While once overfished, it recovered rapidly and is currently responsible for a productive fishery. For this study four stock assessments (Figure 13) were incorporated into the analysis, including Jagielo *et al.* (2000), Jagielo *et al.* (2003), Jagielo and Wallace (2005), and Hamel *et al.* (In press). All assessments
Figure 10. Yelloweye rockfish time series of abundance (upper panel) and variation in abundance (lower panel).

Figure 11. Yellowtail rockfish time series of abundance (upper panel) and variation in abundance (lower panel).
Figure 12. Cabezon time series of abundance (upper panel) and variation in abundance (lower panel).

Figure 13. Lingcod time series of abundance (upper panel) and variation in abundance (lower panel).
reported biomass time series in equivalent units and no standardization was required. Analysis of the data produced 180 log-ratio estimates, with a standard deviation of 0.44.

**Pacific whiting (Merluccius productus)**

Pacific whiting, also known as Pacific hake, has been assessed far more times than any other groundfish stock. It is a gadoid species that undertakes annual migrations along the entire U.S. west coast to summer feeding grounds off Oregon, Washington, and British Columbia. For the meta-analysis time series of spawning biomass from 15 different stock assessments (Figure 14) were summarized (Dorn and Methot 1991, 1992; Dorn et al. 1993; Dorn 1994, 1995, 1996; Dorn and Saunders 1997; Dorn et al. 1999; Helser et al. 2002, 2004, 2005, 2006; Helser and Martell 2007; Helser et al. 2008; Hamel and Stewart In press). The four assessments conducted from 2004-2007 each presented two separate models that differed due to assumptions about the acoustic survey \( q \); these were averaged within each model to produce a single assessment-specific time series for this analysis. Analysis of the 2,498 log-ratio estimates of abundance that were calculated yielded \( \sigma = 0.47 \).

**Sablefish (Anoplopoma fimbria)**

Sablefish is a very important commercial species that is harvested in fixed gear and trawl fisheries operating on the continental shelf and slope. It is found along the entire U.S. west coast. Seven stock assessments (Figure 15) were incorporated into the meta-analysis (Methot 1992; Methot et al. 1994; Crone et al. 1997; Methot et al. 1998; Schirripa and Methot 2001; Schirripa and Colbert 2005; Schirripa 2007). All analyses reported stock size in terms of spawning biomass. However, the 1997 and 1998 assessments presented two and three, respectively, different model scenarios that were blended (averaged) into a single representation for each assessment. From these data a total of 564 log-ratio values were calculated, which yielded an estimated standard deviation of 0.50.

**Dover sole (Microstomus pacificus)**

This flatfish species is a member of the continental slope DTS complex that is harvested by trawl fisheries along the whole west coast. Although the stock has been assessed for many year, only three assessments (Figure 16) were utilized in the meta-analysis due to changing geographic stock definitions. For this study we summarized spawning biomass estimates from Brodziak et al. (1997), Sampson and Wood (2001), and Sampson (2005). Even then a ratio estimate (1967-96) was required to expand the 1997 assessment results (Monterey to US Vancouver INPFC areas) to a coastwide estimate (\( \times 1.42 \)). Following standardization a total of 84 ratio estimates were calculated, with \( \sigma = 0.58 \).
Figure 14. Pacific whiting time series of abundance (upper panel) and variation in abundance (lower panel).

Figure 15. Sablefish time series of abundance (upper panel) and variation in abundance (lower panel).
Petrale sole (Eopsetta jordani)

This is a high-value flatfish species that is taken in trawl fisheries along the entire west coast. It has been fished intensively for decades. We analyzed results from three petrale sole stock assessments (Figure 17), including Sampson and Lee (1999), Lai et al. (2005), and Haltuch and Hicks (In press). Results in all documents are presented as time series of spawning biomass and consequently no standardization to a common abundance metric was required. From the three reports 76 paired abundance ratios were calculated, resulting in a standard deviation of 0.37.

Pacific mackerel (Scomber japonicus)

Pacific mackerel is a CPS species that is fished primarily off the State of California and Mexico in “wetfish” purse seine fisheries. Two update stock assessments were excluded from the meta-analysis, but four other full assessments were included (Hill and Crone 2004, 2005; Dorval et al. 2007; Crone et al. 2009) (Figure 18). All report population abundance in terms of spawning biomass [mt] and no ratio-based standardization was needed. From those four citations 200 estimates of ln(R_i|j,t) were calculated, resulting in σ = 0.69.
Figure 17. Petrale sole time series of abundance (upper panel) and variation in abundance (lower panel).

Figure 18. Pacific mackerel time series of abundance (upper panel) and variation in abundance (lower panel).
Pacific sardine (*Sardinops sagax*)

The last species considered in this analysis is Pacific sardine, which is a very important CPS species that is harvested from Mexico to Canada in purse seine fisheries. We considered three full sardine stock assessments (Figure 19) in the analysis, including Conser *et al.* (2004), Hill *et al.* (2007), and Hill *et al.* (2009). All three assessment documents reported population abundance in terms of spawning biomass over a common geographical area and no standardization of metrics was required. A total of 100 log-ratio estimates were obtained with a standard deviation of 0.40.

![Pacific sardine time series of abundance (upper panel) and variation in abundance (lower panel).](image)

**Synopsis:** Seventeen species were considered in this analysis and individual stock-specific results for all are summarized in Table 1. Also included are the “within” assessment estimates of statistical uncertainty as measured by the asymptotic standard deviation derived from inversion of the Hessian matrix. In order to directly compare the two measures of uncertainty, the log-scale variation among assessments was expressed as a CV on the arithmetic scale according to $CV = (exp[\sigma^2] - 1)^{0.5}$ (Johnson and Kotz 1970). When plotted against one another (Figure 20) it is evident that variation between and among stock assessments is far greater than that within assessments. Note that the among assessment CV for shortspine thornyhead (SST) is far in excess of that measured for any other stock. From that perspective it may be considered an outlier. Moreover, there is
Table 1. Summary of stock-specific analyses of variation in abundance estimates from assessments of groundfish and CPS species.

<table>
<thead>
<tr>
<th>Group</th>
<th>Common Name</th>
<th>Scientific Name</th>
<th>Number of Assessments</th>
<th>Variability “Among”</th>
<th>Variability “Within”</th>
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<td>Rockfish</td>
<td>Yellowtail rockfish</td>
<td><em>Sebastes flavus</em></td>
<td>6</td>
<td>456</td>
<td>0.312</td>
</tr>
<tr>
<td>Roundfish</td>
<td>Cabezon</td>
<td><em>Scorpaenichthys marmoratus</em></td>
<td>3</td>
<td>96</td>
<td>0.296</td>
</tr>
<tr>
<td>Roundfish</td>
<td>Lingcod</td>
<td><em>Ophiodon elongatus</em></td>
<td>4</td>
<td>180</td>
<td>0.436</td>
</tr>
<tr>
<td>Roundfish</td>
<td>Pacific whiting</td>
<td><em>Merluccius productus</em></td>
<td>15</td>
<td>2,498</td>
<td>0.472</td>
</tr>
<tr>
<td>Roundfish</td>
<td>Sablefish</td>
<td><em>Anoplopoma fimbria</em></td>
<td>7</td>
<td>564</td>
<td>0.498</td>
</tr>
<tr>
<td>Flatfish</td>
<td>Dover sole</td>
<td><em>Microstomus pacificus</em></td>
<td>3</td>
<td>84</td>
<td>0.576</td>
</tr>
<tr>
<td>Flatfish</td>
<td>Petrale sole</td>
<td><em>Eopsetta jordani</em></td>
<td>3</td>
<td>76</td>
<td>0.366</td>
</tr>
<tr>
<td>CPS</td>
<td>Pacific sardine</td>
<td><em>Sardinops sagax</em></td>
<td>3</td>
<td>100</td>
<td>0.403</td>
</tr>
<tr>
<td>CPS</td>
<td>Pacific mackerel</td>
<td><em>Scomber japonicus</em></td>
<td>4</td>
<td>200</td>
<td>0.689</td>
</tr>
</tbody>
</table>
not a significant correlation between CVs, whether the SST data are retained ($r = -0.31$, $P = 0.23$) or excluded ($r = -0.20$, $P = 0.45$). Figure 21 shows the distribution of CVs with SST removed. If considered independent, the mean and standard deviation of among assessment CVs is 0.510 and 0.187, whereas for within assessment CVs these statistics are 0.187 and 0.089, respectively.

Figure 21. Frequency distributions of coefficients of variation among and within groundfish and CPS assessments (SST removed).
Pooled Results

The PFMC’s groundfish FMP includes approximately 80 species and ACLs will need to be established for all species that are in the fishery. Of the stocks listed in the FMP, only about 25-30% have been assessed using dynamical population models, e.g., Stock Synthesis (Methot 2000). Importantly, a number of species have only been assessed once, so that among assessment variation cannot always be estimated, even when an assessment has been conducted. There is, consequently, some merit in pooling results from the well-studied species described here in order to develop proxy relationships for all groundfish and CPS stocks, even those that have been assessed multiple times.

Three natural groupings exist for the groundfish species we have summarized, which are classified in the FMP as rockfish, roundfish, and flatfish. In Table 1 each of the 15 groundfish stocks we considered is assigned to one of these three species groupings. In a similar manner, the two CPS species were grouped together. Note that for this analysis we excluded shortspine thornyhead from the rockfish group due to its extremely large coefficient of variation (Figure 20) and its degenerate tri-modal distribution of $\ln(R_{ij})$ values (Figure 8). Pooling of stocks was accomplished by equally weighting each species in the group, so that stocks that were assessed many times (e.g., canary rockfish, Pacific whiting, and sablefish) did not unduly influence the composite result.

Results presented in Figures 22-25 show the composite frequency distributions for each of these four stock groupings. Also shown in each figure is the estimated standard deviation of the distribution, which could serve as a proxy measure of uncertainty for species that were classified in the group. Specifically, estimates of the standard deviation of the $\ln(R_{ij})$ were 0.486, 0.464, 0.507, and 0.463 for rockfish, roundfish, flatfish, and CPS, respectively. Clearly there is marked similarity in these estimates of $\sigma$.

Note also that three of the four distributions, especially flatfish and CPS, retain a bi-modal character to the combined data. This indicates that repeat assessments tend to primarily scale the population trajectories up or down, i.e., they do not cross one another.

Given the similarity in parameter estimates across the four stock groups, we further aggregated the information into a single group, again with shortspine thornyhead excluded. We present results where all species are equally weighted (Figure 26) and all species groups are equally weighted (Figure 27). The standard deviations of the $\ln(R_{ij})$ values in these two analyses were identical to the third decimal place ($\sigma = 0.480$), reflecting the similarity of the parameter estimates from the four stock grouping analysis. The fit to the data when species are weighted equally (Figure 26) is marginally better (SSD = $3.25 \times 10^{-4}$) than when the four species groups are equally weighted (Figure 27; SSD = $1.12 \times 10^{-3}$). The better fit is reflected in a more unimodal character to the distribution.
Figure 22. Composite distribution of $\ln(R_{ij,t})$ values for rockfish stocks ($Sebastes$ spp.).

Figure 23. Composite distribution of $\ln(R_{ij,t})$ values for roundfish stocks (cabezon, lingcod, Pacific whiting, and sablefish).
Figure 24. Composite distribution of $\ln(R_{ij,t})$ values for flatfish stocks (Dover and petrale soles).

Figure 25. Composite distribution of $\ln(R_{ij,t})$ values for CPS stocks (Pacific mackerel and sardine).
Figure 26. Composite distribution of $\ln(R_{ij,t})$ values for groundfish and CPS stock, each equally weighted.

Figure 27. Composite distribution of $\ln(R_{ij,t})$ values for the equally weighted four stock groupings.
Discussion

We have summarized within and among levels of variation in 17 groundfish and coastal pelagic species stock assessments that have been conducted over the last 20 years for the Pacific Fishery Management Council. Our findings show the somewhat startling result that there is a remarkable level of consistency in the variation among stock assessments when viewed retrospectively. Whether individual stocks are considered independently of one another, four distinct stock groupings are evaluated, or all 17 stocks are pooled together, the amount of variation among stock assessments is largely consistent (Figure 21). It is particularly noteworthy that the four stock grouping analysis and the fully pooled analysis both resulted in estimates of $\sigma \approx 0.50$.

To illustrate how this parameter estimate can be used to quantify scientific uncertainty we argue that the standard deviation of the $\ln(R_{ij})$ values represents a proxy for model specification imprecision. We further note that, following aggregation, a lognormal distribution fits the data very well (e.g., Figure 26). Back-transformation to the arithmetic scale of a lognormal distribution with $\sigma = 0.50$ results in the relationship depicted in Figure 28. Note that half of the probability density is below a value of 1.00, which represents the mode of the distribution. One can then select a cumulative probability less than 0.50 that maps onto a multiplier that can be interpreted as a reduction from the point estimate of the mean of the distribution. For example, 40% of the probability density is found at values $\leq 0.881$ (-0.127 on log-scale). If one assumes that the mode of the lognormal distribution (1.00) is indicative of the best point estimate of catch (= OFL), 88% of that amount would associated with a 0.40 probability of exceeding that quantity. Of course an actual policy decision will need to be made as to an appropriate level of $P^*$ (the probability of overfishing), whether it be 0.40 or some other value. Likewise, this simple example does not include scientific uncertainty attributable to within assessment variability (statistical measurement error), although all the necessary components are available in Table 1 to blend the two sources of error.

![Figure 28. Relationship between the probability of overfishing ($P^*$) and an appropriate buffer between the ABC and the OFL, assuming only that $\sigma = 0.50$.](image-url)
Acknowledgments

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